

HUMMOCKY AND FLUTED MORAINES IN PART OF NORTH-WEST SCOTLAND

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ABSTRACT

This thesis is concerned with the formation and significance of moraines produced c. 11,000-10,000 yrs. B.P. by the glaciers of the Loch Lomond Advance. The moraines have a variety of forms but they have previously been divided into two groups: fluted and hummocky moraines. Fluted moraines have been shown by previous work to be subglacial landforms produced by active ice whereas the majority of hummocky moraines have been attributed to deposition from the surface of stagnant ice.

The methods employed include field mapping and morphological interpretation but the most important data are derived from measuring the particle-size distribution, rock-type composition and other characteristics of the till.

Groups of samples are taken from several groups of fluted moraines. Changes in the properties of the till at different parts of the ridge, between members of a group of ridges, and between ridges and underlying or adjacent till are discussed. The features studied have a variety of sizes but they are generally on a scale that has rarely been described in previous literature, being intermediate between large-scale and small-scale features.

Associations between fluted moraines and hummocky moraines in the field area raised the suspicion that some of the latter may have been formed subglacially. Detailed sampling revealed that all the hummocky moraines studied contain a large proportion of material that was picked up from the valley floors and carried only a short distance during the Loch Lomond Advance. These findings together with other evidence lead to the firm conclusion that the hummocky moraines studied were produced by active ice. This conclusion is accompanied by discussion of the mechanisms by and conditions under which the moraines could have been formed and could have survived. It is suggested that the material was, at least in part, pushed up by the advancing ice front and subsequently passed over by the ice which reworked it to varying degrees.

Acknowledgments

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CHAPTER 1

INTRODUCTION

Since J. B. Simpson's (1933) publication, a large volume of work by J. B. Sissons, his students and others has been devoted to mapping glacial features formed by the Loch Lomond Advance, inferring the limits of the glaciers that produced these features and hence the patterns of ice-flow that occurred. Other work has dealt with the climate and environment of the Loch Lomond Stadial. Thus we have a good knowledge of the events of the period. This thesis builds on that knowledge to study the processes that formed the hummocky and fluted morainic features that are a widespread result of that glacial event. It therefore seeks to contribute to the difficult subject of glacial processes where lack of knowledge of former environments and difficulties of observation on modern glaciers has limited our understanding.

The area around Glen Torridon was chosen for the work because it has relatively good access by road and path and because earlier workers (Robinson 1977, Sissons 1977a) had reported a diversity of striking morainic features. A third advantage was that the geological situation favoured the tracing of erratics and this proved to be one of the most important methods employed in the project. Since exposures of the interiors of the moraines are sparse the fieldwork depended heavily on the manual digging of pits, which were usually a little over 1 m deep. Sampling of the till at different depths within the pits and, where possible, from other sources helped

to assess their representativeness of a greater depth of till.

Since this thesis has one subject and one aim its structure is fairly simple. The three chapters which follow this one summarise the background against which the project is set. Chapter 2 introduces the field area and the state of knowledge about the Lateglacial period as it relates to that area. Chapter 3 contains a rationale of the project, discusses the state of our knowledge about fluted and hummocky moraines and highlights contributions that the study can make to these and other problems. Chapter 4 explains the techniques and methods employed.

The five subsequent chapters comprise the main body of the thesis, being a presentation of the data collected. Each of the first three of these chapters is devoted to a consideration of the events within one drainage basin and the fourth (Chapter 8) concerns four smaller areas. In order to improve the continuity of the thesis the results presented in these four chapters are discussed immediately after their presentation. Chapter 9 deals with the data from the four previous chapters as a whole and introduces other data that could not be conveniently incorporated in them. Since this chapter immediately precedes the final discussion (Chapter 10), which also deals with the project as a whole, discussion of the results given in Chapter 9 is relatively brief. The final chapter includes a speculative discussion in which the evidence presented in the thesis and other relevant facts and opinions are brought together to extend the explanation offered. It also includes an inventory of the features studied and a summary of the general conclusions and implications of the thesis.

CHAPTER 2

THE PHYSICAL CONTEXT OF THE STUDY

2.1 Introduction

Many theses are introduced by detailed accounts of diverse aspects of the field area. This is relevant to comprehensive studies of the geomorphology of a region but in this study attention is concentrated on the formation of certain moraines: consequently only those aspects considered important to the study are described here. Thus the aim of this chapter is to introduce the physical background of the thesis by describing the relief, geology and glacial history of the study area and discussing the conditions that occurred during the Lateglacial period.

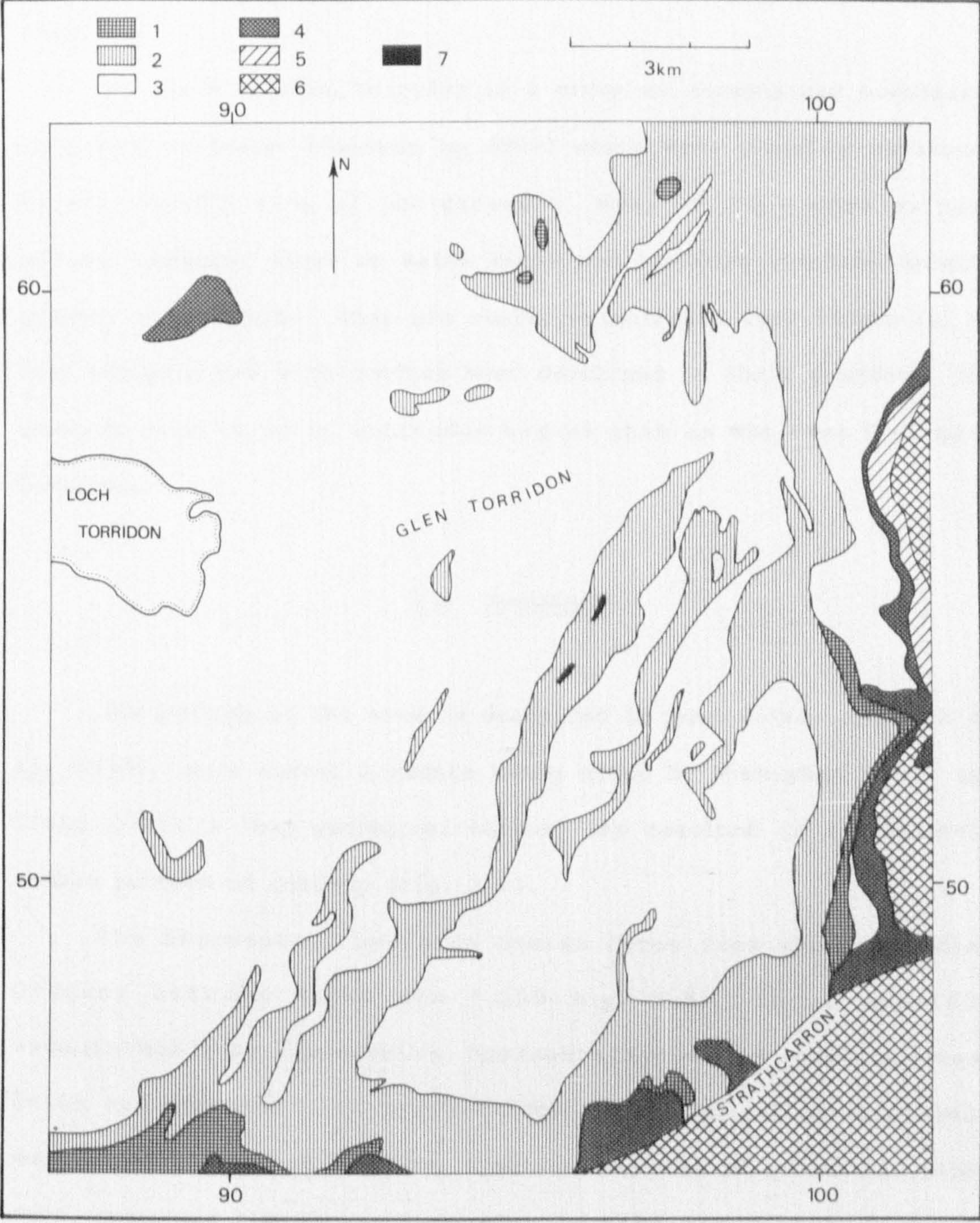
All the detailed fieldwork was carried out in the area shown in Fig. 2.2 but some parts of this area were not studied and observations from other parts of Scotland are included. A full account of the reasons for working around Glen Torridon is given in Chapter 3. This can be summarised by stating that the variety and profusion of moraines, the favourable bedrock pattern and the existence of background knowledge were all important factors.

2.2 Relief

The area comprises two mountain masses, N and S of Glen Torridon. In the southern section valleys run out radially from an undulating core area around Meall Dearg (646m) and are overlooked by

Fig. 2.1 The geology of the field area

1. Cambrian limestone, Sepulite grit and
Fucoid beds
2. Cambrian Pipe Rock and Basal Quartzite
3. Torridon Sandstone
4. Lewisian Gneiss
5. Mylonised rocks
6. Moine Schist
7. Felsite dykes



ridges which rise, in five places, to over 900m. The ridges bear some large corries and in places they have been breached, apparently by the coalescence of corries. The corrie floors are often at about 500m O.D.

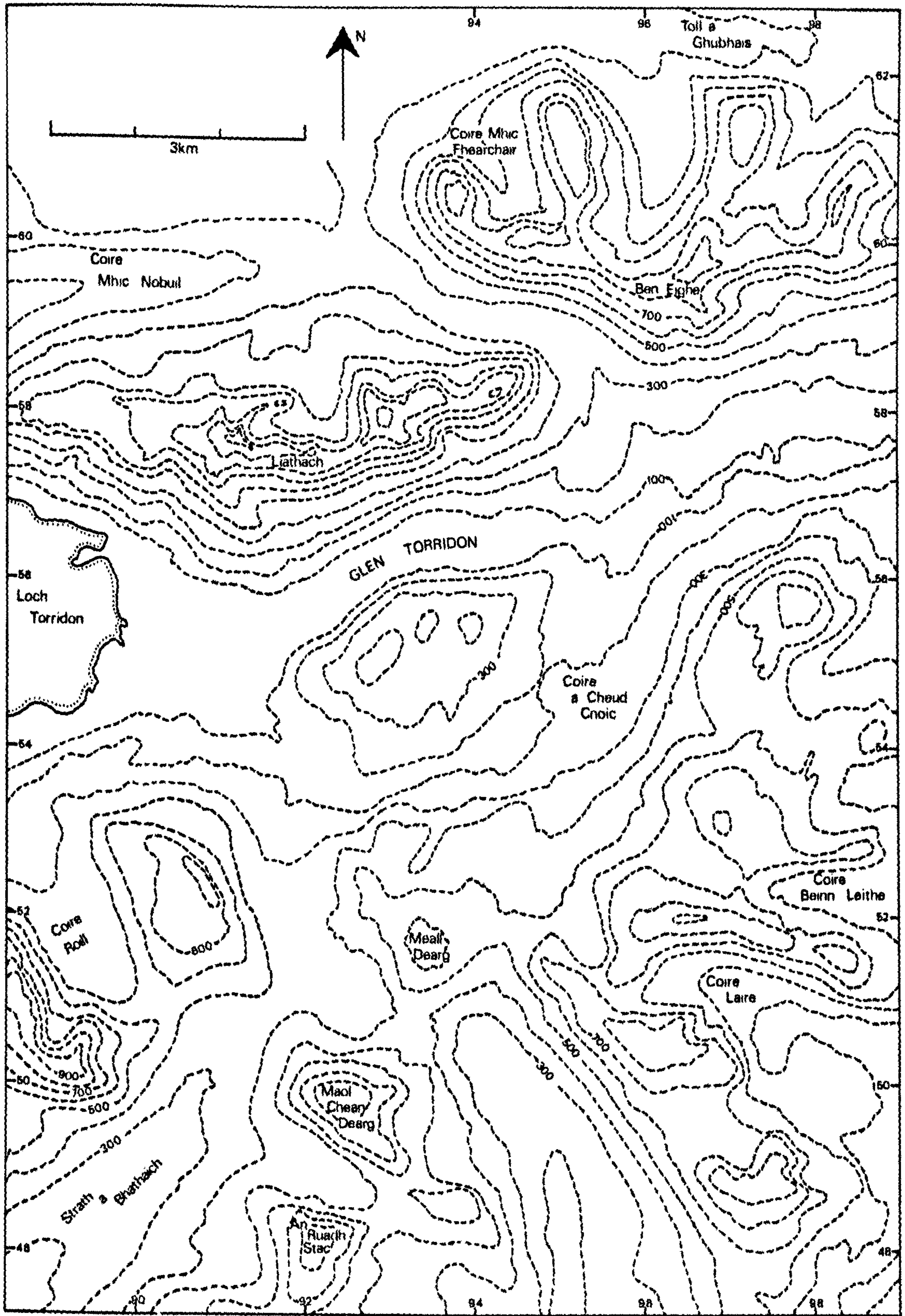
To the N of Glen Torridon is a group of steep-sided mountains, separated by deeper breaches (c. 400m) which were probably excavated by the through flow of ice streams. Many of the mountains have several summits, those on Beinn Eighe and Liathach reaching heights greater than 1,000m. They are characteristically long ridges (up to 7km) trending E-W with corries best developed on their N sides. The corries tend to be at altitudes higher than in the area S of Glen Torridon.

2.3 Geology

The geology of the area is described in most detail by Peach et al. (1907), more recent accounts being given by Phemister (1960) and Craig (1965). A long geological history has resulted in a relatively simple pattern of outcrop (Fig. 2.1).

The basement of Lewisian Gneiss dates from the Laxfordian Orogeny between 1,600 and 1,200 m.y. B.P. It is overlain unconformably by the massive, horizontally-bedded conglomerates, grits and sandstones of the Torridon sediments, which are again succeeded unconformably by the Cambrian sequence of quartzite, pipe-rock, grits and limestone. This stratigraphy was disrupted during the Caledonian Orogeny at which time Schists of the Moine Series were thrust westwards (in relative terms) towards the area. Nappes of Lewisian Gneiss were incorporated in this movement and occur near the

Fig. 2.2 The topography of the field area



outcrop of the Moine Thrust Plane, while Torridon and Cambrian sediments have been thrust over one-another along several planes in advance of it. Thus the quartzite crops out in a series of narrow bands orientated NE-SW across the area. Lewisian Gneiss in its original basement position appears only as a small inlier in the NW of the area. Since bedrock exposure is extensive "uncertain" sections of bedrock contacts (on geological survey maps) are usually short. Two short sections of felsite dyke are exposed but elsewhere igneous rocks are absent.

2.4 Glaciation

Robinson (1977) gave a summary of the development of ideas concerning the glacial history of the area. She noted that, despite Charlesworth's detailed but unsubstantiated work (1955), Peach et al. (1913) were followed by Phemister (1960) and that the view expressed in both these publications was that there had been three phases of glaciation: (i) maximum glaciation with ice flowing over all mountain tops in the area in a NW direction, (ii) the Confluent Glacier Phase when two ice masses emanating from the Fannichs to the NE and the Monar basin to the SE were confluent somewhere along Glen Torridon and (iii) The Valley Glacier Stage represented by moraines in the valleys.

Since 1960 a great deal of work in the area and elsewhere in Great Britain has developed our understanding of the sequence and suggested a similar three part history.

2.4.1 The Loch Lomond Advance

This event was previously called the Loch Lomond Readvance but, since the evidence favours complete deglaciation during the Lateglacial Interstadial, Loch Lomond Advance is used in this thesis (following Sissons 1977a). It is by far the best established event subsequent to maximum glaciation, being evidenced by moraines in many parts of upland Britain. Radiocarbon dating has shown that some of these moraines accord with the only major cold period, recorded in the stratigraphic record, since The Late-Devensian glacial maximum. In examples where absolute dating is not possible the fact that no subsequent glacial events are recorded by deposits up-valley of the limits has been used to assign the features to this last cold period (termed the Loch Lomond Stadial).

In the study area the glacier limits of this period are often represented by marginal moraines the largest of which is 20m high. In some valleys there are up to three additional ridges within a short distance of the limit but beyond this zone end moraines are absent except, possibly, in one valley (Section 6.1.2). In most cases the end moraines are succeeded up-valley by mounds and ridges that have been classified as fluted and hummocky moraines by Sissons (1967) and other workers (Chapter 3).

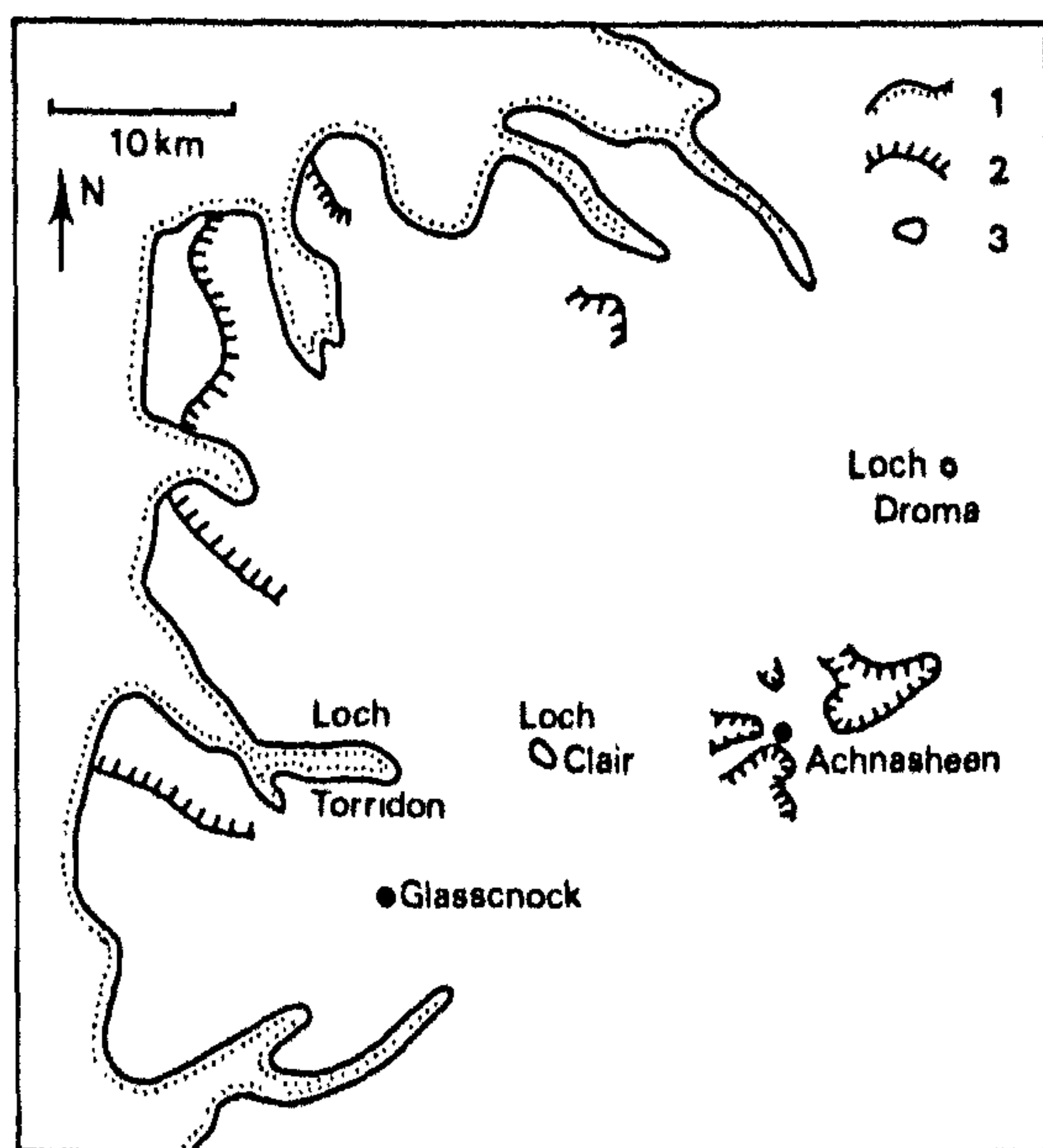
Fluted moraines are smooth subdued ridges sometimes over 100m long. They may be straight or gently curving and run parallel to one-another in groups to form a corrugated pattern. Their amplitude is varied: some features are less than 1m high but 10-20m wide, others can only be detected on aerial photographs, but the largest features are 5m high with steep sides. Hummocky moraines are

Fig. 2.3 Glacial readvance limits and
locations referred to in the text

- 1 Coast
- 2 Glacial limits
- 3 Lochs

unstratified, undulating, disordered mounds. They vary in amplitude, being up to 10m high; in steepness of slopes, being up to 40°, in sharpness of crests; in boulder content and in their spacing.

This two-fold division has been useful in mapping areas formerly covered by glaciers since fluted moraines give evidence of ice flow directions whereas hummocky moraines have been used to define the limits of those glaciers where end moraines are absent. However, most of the detailed accounts of the features (see Section 3.4.2) reveal that there is a wide variety of features in each class and that some features have characteristics of both groups. Despite this complication the terms hummocky and fluted moraines are used here because they are well established descriptive names and any subdivision of the groups or introduction of new terms would be confusing and arbitrary.



Local confirmation of the age of the features mentioned above is provided by the results of pollen analysis from two basins a short distance inside and outside an end moraine at Glassnock (Fig. 2.3) and radiocarbon dating of the sediments in the outer site (Robinson 1977). Further

evidence is derived from the presence of an unknown number of varves at the base of a post-glacial (Flandrian) pollen sequence from Loch Clair (Fig. 2.3) in the E part of the area (Pennington et al. 1972).

2.4.2 Other glacial stages

Robinson (1977) described a large lateral moraine on the Applecross peninsula. She interpreted this feature as having been formed by a lobe of ice occupying Loch Torridon during the retreat of the Late-Devensian ice sheet. Subsequently Robinson and Ballantyne (1979) described marginal moraines on the peninsulas N of Applecross. These features, including that on Applecross, total nearly 30km in length and striae change their orientation at the limits. Corries, for instance on An Teallach, were not ice sources when the moraines were formed. The authors interpreted the features as evidence of a readvance during deglaciation, naming it the Wester Ross Readvance, although the possibility that the Applecross moraine related to an earlier stage was not ruled out.

More recently Sissons (in press) has described the formation of an ice-dammed lake at Achnasheen, E of the Torridon area. The lake was held up by two E-flowing glaciers and one S-flowing glacier (Fig. 2.3). There is evidence that the events represent a readvance of at least 5km by the S-flowing glacier (The Achnasheen Readvance) and it therefore seems likely that the steep ice margin positions of the E-flowing glaciers also represent the culmination of a readvance. Sissons also presented evidence that a small glacier independent of the main ice masses existed at this time and described one terminal moraine to the SE which was probably formed at an earlier stage.

Thus it can be concluded that there is evidence of three phases in the glacial history of the area: (i) maximum glaciation, (ii) an unknown number of readvance stages during retreat and (iii) a

separate advance of valley glaciers.

2.5 Chronology, conditions and events of the Lateglacial period

The glacial history described above can be related to other evidence to provide a more detailed impression of the Lateglacial period but the exercise is hampered by deficiencies in the two main sources of evidence. (i) Radiocarbon dating is prone to certain errors, particularly in newly deglaciated areas where dates tend to be too old (Sutherland 1980). They are not accurate enough to determine the duration of a short event c. 10,000 yrs ago. (ii) It is difficult to make climatic inferences from pollen analysis particularly for glacial periods when the record is sparse and at the end of such periods when recolonisation is dependent on other variables as well as climate.

The oldest radiocarbon date from this part of Scotland is 12,810 \pm 155 B.P. from Loch Droma (Fig. 2.3) (Kirk and Godwin 1963) but it is not clear whether the site was ice-covered at the time of the readvance stages referred to above.

During ice-sheet retreat in the field area one can envisage a gradual lowering of the ice surface and a reduction in the vigour of the north-westward flow as local topography exerted a greater influence. The ice sheet may have down-wasted to leave separate masses of ice stranded in the valleys. But the evidence cited above for readvances to the E, W and N of this area suggests that a more active period of deglaciation occurred. The fieldwork area may have nourished some of the glaciers responsible for these readvances in

which case a more radial pattern of flow out of the area would have developed. However, beyond the limits of the Loch Lomond Advance, there are no radially-directed striae or other evidence for this possibility.

Robinson (1977) presented a series of five radiocarbon dates from sediments at Glassnock. The basal date is out of sequence and therefore in error but the second date is $11,161 \pm 350$ B.P. A third date marks the onset of the Loch Lomond Stadial at $10,060 \pm 560$ but clearly little can be inferred about the duration of the Lateglacial Interstadial since the latter date at least has a very large error factor. Pollen evidence from the same site indicates a dwarf-shrub heath vegetation and implies an increasingly oceanic climate during the interstadial.

Pollen and Coleopteran evidence from elsewhere indicate that the climate deteriorated gradually during the Lateglacial Interstadial, with some sites giving evidence of a minor fluctuation (Older Dryas) and others recording two sharp steps in the decline.

The best local evidence for the climatic conditions during the Loch Lomond Stadial is derived from the equilibrium firnline heights of the glaciers that formed at that time. Robinson calculated these to average 409m O.D. in the Applecross area and 474m farther E; from these firnlines she inferred a mean sea-level summer temperature of c. 4°C . During the stadial permafrost existed down to sea-level in Scotland, the most notable local evidence being a fossil frost wedge (3m deep) just inside the limit of a glacier c. 30km N of Glen Torridon (Sissons 1977a).

Some pollen evidence for climatic fluctuations during the stadial is available. Pennington (1977), on the basis of work in NW

Scotland, proposed a severe phase lasting until c. 10 400 B.P., this being succeeded by a milder period lasting until the start of the Flandrian at 10,000 B.P. Lowe and Walker (1980) agreed that if their radiocarbon dates for an early deglaciation of the Rannoch Moor area were accepted (see below), the climate was likely to have warmed at c. 10,400 B.P. MacPherson (1980) recognised three phases at a site on Speyside, comprising an oceanic period at the start of the stadial and another at the end, separated by a more continental phase with fewer snow patches. There is general agreement in the pollen and Coleopteran evidence that the climate improved dramatically at the end of the stadial.

It is difficult to assign dates to the Loch Lomond Stadial or, more important in the context of this study, to estimate its duration. This is because radiocarbon dates from different sites are contradictory and the event was probably time transgressive. Dates of 10,800-10,300 B.P. have often been assigned to the stadial and the dated deposits show that it was certainly no later than this. Sissons (1979) suggested that with climatic deterioration during the Lateglacial Interstadial glaciers could have returned to Scotland by 11,500 B.P. Radiocarbon dates as old as $10,660 \pm 240$ B.P. have been recorded for sediments deposited after the deglaciation of Rannoch Moor which was at the centre of the largest Loch Lomond Advance ice mass (Lowe and Walker 1980). The authors treated these dates with caution because they are probably prone to errors that tend to make them younger (Sutherland 1980). Stronger evidence of glacier retreat before 10,600 B.P. has been found by Pennington (1975) in the English Lake District. Here deposits of the Artemisia pollen phase

are found at two sites within the limits of Loch Lomond Advance glaciers. The end of this pollen phase is dated at $10,650 \pm 170$ B.P. in a nearby site that was not covered by Loch Lomond Advance ice.

The duration of glacier ice in lake catchments has been inferred from varved lake sediments in the English Lake District where there are from 400 to 450 varves (Pennington 1978). In Loch Ness there are far more varves although the full sequence was not sampled (Pennington et al. 1972).

The glaciers formed during the Loch Lomond Advance and also their deposits have been used to make climatic inferences about conditions during the stadial. As mentioned above Robinson (1977) has used the equilibrium firnline altitude of the former glaciers in the area S of Glen Torridon to estimate mean summer temperatures. This type of work has been developed by Sissons and carried out in other areas, details of the method and its assumptions being given (e.g. Sissons 1974a). It has resulted in general inferences, such as the prevalence of SE snow-bearing winds during the stadial (Sissons 1980), and other temperature estimates e.g. mean summer temperatures (at sea-level) of 6°C in the SE Grampians (Sissons and Sutherland 1976) and 7°C in the SW Grampians (Sissons 1979a). Such estimates are in accord with Coope's coleopteran evidence from farther S. In association with evidence for discontinuous permafrost at sea-level in Scotland, which indicates a mean annual temperature no higher than -1°C , they imply a greater annual temperature range than at present (Sissons 1979a).

Some weaker palaeoclimatic inferences stemming directly from the morphological evidence have been made. The Loch Lomond Advance glaciers left a limited variety of terminal features: some produced

no end moraines, some produced a single ridge (occasionally up to several hundred metres broad), and others produced several moraines in a terminal zone up to several hundred metres wide. Up-valley of all these types of feature it is unusual to find any further ice-marginal features except in some valleys in the English Lake District and North Wales where retreat moraines occur.

Around the Gaick plateau Sissons (1974a) noted a general absence of end moraines and attributed this to climatic amelioration before the glaciers reached their maximal extents, resulting in them occupying that extent for a very short time. In more general terms Sissons (1974b) attributed climatic significance to the widespread repetition of the pattern of multiple end moraines in a narrow terminal band, suggesting that it indicates slight amelioration, perhaps interrupted by cold periods, before the very rapid climatic improvement, proposed by Coope and others, caused rapid deglaciation. Hummocky moraines have been assumed to have been formed during rapid deglaciation e.g.:

"Extensive spreads of hummocky moraine within these outlet valleys and on the floor of the Rannoch Basin itself, indicate that the Loch Lomond Readvance glaciers wasted and decayed in situ, probably in response to the rapid rise in temperature" (Walker and Lowe 1977 p. 347).

2.6 Conclusion

The above discussion leads to more speculative considerations that are of greater relevance to this thesis such as the speed and manner of glacier advance during the Loch Lomond Stadial, the thermal

regime of the glaciers and the pattern of deglaciation. these matters will be dealt with in the concluding discussion (Chapter 10).

At this stage it is sufficient to note that the Loch Lomond Advance was the last glacial event in Scotland. It differed greatly from the preceding ice-sheet glaciation; it was brief, its extent is well marked and something is known about the climatic conditions of the time.

CHAPTER 3

THE THEORETICAL CONTEXT OF THE STUDY

3.1 Introduction

This chapter evaluates the advantages and disadvantages of this study in comparison with studies of deposits formed by contemporary glaciers and by past glacial events. The study is also evaluated in terms of its usefulness and relevance to various areas of research. The state of our knowledge in these research fields is outlined to identify the contributions that this study can seek to make.

3.2 Rationale of the project

Much work on glacial deposits takes place in areas close to, and recently covered by, contemporary glaciers and in areas formerly covered by continental ice-sheets. Alaska, Spitzbergen, Norway and the Alps are typical areas for the first type of investigation while North America and Scandinavia are the main areas for the second type of work. It is suggested in this section that this project has advantages over both these types of study.

The geomorphologist working in Britain has access to excellent background information. The following sources have been of particular importance in this study: (i) the recent series of photogrammetrically-contoured, 1:10,000, Ordnance Survey topographic maps on which very minor geomorphic features are often marked by

small indentations in the contours, (ii) comprehensive aerial photographic coverage available for viewing and for purchase, (iii) the Geological Survey maps and memoirs.

Important advantages stem from working on deposits of the Loch Lomond Advance. As described in the previous chapter this was a simple glacial event lasting about 1,000 years. Thus it is possible to think of glaciers advancing to their maximal extents and then retreating. This situation is preferable to that prevailing in front of contemporary glaciers that have probably existed throughout the present inter-glacial and may have experienced several minor advances and retreats during that period. It is also preferable to the situation in areas last covered by an ice-sheet since an ice-sheet glaciation is a relatively major and complex event. The Loch Lomond Advance is also the most recent glacial event in Britain so its products have not been modified by any subsequent glacial or severe periglacial agencies. The fact that glaciers are no longer present allows the whole catchment area to be inspected so that the geology of the source area and the distribution and composition of till throughout the area covered by a given glacier are known. A great quantity of other work has been concentrated on the conditions of the Loch Lomond Stadial (see Sissons 1979b) and this provided valuable background information.

In the study area the work of Sissons (1977a) and Robinson (1977) has been useful in locating and mapping depositional features, in inferring the maximal extent of the former glaciers and in reconstructing, from the available evidence, the glacier surfaces at that time. They showed that the Loch Lomond Advance in this area was represented by a number of valley glaciers and small ice-caps and

that there is a wealth of various types of hummocky and fluted drift topography in the valleys.

Another major advantage specific to this area is the nature and distribution of bedrock lithologies and their relationship to ice movements. During the Late-Devensian and, presumably, earlier ice-sheet glaciations ice moved over the area from the E transporting with it Moine Schist and Lewisian Gneiss from beyond the Moine Thrust Plane. All the Loch Lomond Advance glaciers studied were situated W of the Moine Thrust Plane and most of the bedrock in this area is composed of Torridon Sandstone and Cambrian Quartzite. These latter rock-types are easily distinguishable from each other and from the rocks derived from E of the Moine Thrust Plane. Thus for any sample of till all the clasts can be assigned to one of three classes, (i) Torridon Sandstone, (ii) Cambrian Quartzite and (iii) schists and gneisses which are here termed ice-sheet erratics. Since the nearest outcrops of schist and gneiss are several km to the E (Fig. 2.2) such ice-sheet erratics could only have accounted for a small proportion of the debris present before the Loch Lomond Advance. Thus the occurrence of such clasts in the till indicates that a proportionate volume of sandstone and quartzite clasts must also have survived that glaciation. Fig. 2.2 shows that the outcrops of quartzite comprise a series of narrow bands. These often form higher ground or strips across valley floors, allowing the debris in the deposits to be traced to specific sources.

The fact that the features are in a sparsely populated mountain region is advantageous because they have not been disturbed by man but it has an adverse result in that there is an absence of man-made

sections. Other disadvantages are as follows. (i) Since the features are c. 10,000 years old there is a danger that particle-size characteristics, topography and stone orientations may have been altered by post-depositional processes. (ii) The growth of peat in hollows masks the true topography and makes sampling of these areas difficult. (iii) The presence of heath vegetation makes observations less easy than on glacial forelands but is preferable to the forest vegetation of much of Canada and Scandinavia.

3.3 Previous work on fluted moraines

Groups of till ridges parallel to each other and to the former direction of ice movement have been given a variety of names (see Table 3.1). They range from <0.5m to 25m in height (Flint 1971) and from several tens of metres to several kilometres in length. They have been subject to study, comment and speculation in a considerable number of publications.

There are several reasons for this volume of interest. The landforms are some of the most characteristic and orderly features in many glacial landscapes. Because of this they lend themselves to detailed morphological and distributional study. Furthermore, detailed understanding of their mechanism of formation could contribute to the wider problems of genesis of ice-moulded landforms.

In Table 3.1 and much of this section the features are divided into "large-scale" and "small-scale" (<0.5m high and 200m long) groups following Heikkinen and Tikkanen (1979). Most previous work has concentrated on small-scale, ephemeral features that have been revealed in front of retreating glaciers. These features offer the

freshest evidence and can even be traced under the glacier. Since they are small they lend themselves to very detailed study.

Despite the fact that such small features do not occur in the field area a brief review is made here of the most important contributions since the formation mechanisms suggested may be of relevance to the larger features which do occur in the field area. Prior to this review a table of nomenclature is given and the problem of definition is discussed.

3.3.1 Terminology

Table 3.1 Previous nomenclature of ice-moulded grooves and ridges

<u>Author and date</u>	<u>Name of feature</u>	<u>Description of feature</u>
Chamberlin	1888 flutings	furrows in stoss sides of bedrock hills
Gilbert	1904 fluted moraines	small-scale till ridges
Chamberlin	1940 fluted moraines	small-scale till ridges
Smith	1948 flutings	large-scale bedrock grooves
Nicholas & Miller	1952 glacial grooves	small-scale grooves in till
Dyson	1952 Ice-ridged moraines	small-scale till ridges
Hoppe & Schytt	1953 fluted moraine surfaces	small-scale till ridges
Gravenor & Meneley	1958 glacial flutings	large-scale till and bedrock ridges
Lemke	1958 narrow linear drumlins	large-scale ridges of poorly-sorted sand, gravel and till
Strøm	1963 patterned	small-scale till ridges

		marginal plain	
Peacock	1967	moraine features aligned in the direction of ice flow	large-scale till ridges
Sissons	1967	fluted moraines	large-scale till ridges
McPherson & Gardner	1969	fluted lodgement till	short till ridges (2m high) on stoss and lee sides of boulders
Baranowski	1970	fluted moraines	small-scale till ridges
Andersen & Sollid	1971	flutings	small-scale till ridges
Boulton	1971	fluted lodgement till	short till ridges (2m high) with rock cores
Shaw & Freschauf	1973	glacial flutings	large-scale till ridges
Paul & Evans	1974	flutes	small-scale ridges of deformed waterlain sediments
Boulton	1976a	glacially fluted surface, flute	small-scale till ridges
Morris & Morland	1976	glacial flutes	small-scale till ridges
Lawson	1976	fluted moraines	small-scale till ridges
Aario	1977a	glacial flutings	large-scale till ridges
Funders	1978	glacial flutings	large-scale till ridges
Heikkinen & Tikkanen	1979	glacial flutings	large-scale till ridges and erosional bedrock grooves
Karlen	1981	flutes	small-scale till ridges

In none of the above investigations is the choice of name justified or the features to which it applies closely defined. In an article on moraine nomenclature Prest (1968) referred to an orderly gradation from drumlins through narrower drumlinoid ridges to glacial

flutings. He distinguishes the last (fluted ground moraine) from drumlinised ground moraine because the ridges are narrower, more closely spaced and lower (1-1.5m) and because the ridge tops are more or less at the same level as the surrounding ground moraine. In a paper on classification and terminology Aario (1977a) considered it more logical to treat genetically related assemblages as an association of forms rather than to split them into a number of artificial units. He recognised a gradational series from a fluting assemblage into a drumlin assemblage and further into an active-ice hummocky assemblage. Both these authors aim at a morphological classification but their descriptions are not precise enough for the terms to be adopted.

Two definitions of terms were offered by Flint (1971) and Price (1973). The former defined fluted surfaces as "straight parallel grooves with intervening ridges" (p.69). The latter defined fluted ground moraine as "a distinct lineation approximately parallel to the former direction of movement of the glacier or ice-sheet by which it was deposited" (p.78). Embleton and King (1975) used the terms fluted moraine and flutings interchangeably and referred to the small-scale features as micro-flutings but they did not offer any definitions.

All the foregoing information shows that Boulton (1976) was right to point out that the terms used are all descriptive and that they have been defined very loosely. He was also right to suggest that a genetic classification should be aimed at. In accord with this suggestion he defined the processes creating the features that he had investigated and proposed that the term flute should only be applied to those features that originate in the following manner:

"subglacial materials are intruded into tunnels which open up on the lee sided of single, rigid obstructions",

to produce:

"fields of parallel ridges in deformable subglacial surfaces" (p.309).

From this detailed genetic definition of the features it is clear that he was not including large-scale flutings in which "single rigid obstructions" are not usually present, indicating that other processes must be important in their formation. It is therefore suggested here that Boulton's proposal to apply the term flute only to those features that originate in the manner quoted above would usurp the only commonly understood adjective for describing a field of parallel grooves and ridges and that his proposal of a genetic classification is premature, because his paper only explains a subset of these features whose significance is limited by their scale and rapid degeneration.

Thus in this thesis the term fluted moraine will be used for all groups of till ridges parallel to the direction of ice movement. This term was first used for Scottish features by Sissons (1967) and has gained general acceptance.

3.3.2 Formation

Many workers have sought to determine the modes of formation of small-scale fluted moraines. The first of these was by Dyson (1952) at a time when the main debate had centred on whether the features were formed by deposition or by erosion of the intervening grooves. He proposed four mechanisms.

(i) Direct deposition from the ice. He suggested that if this process operated the ridges should get wider down-ice and that some ridges should occur on bare bedrock, but he observed neither of these characteristics.

(ii) Erosion of intervening grooves. He considered that if erosion had occurred it would have removed the small cobbles found at the heads of the ridges.

(iii) Till, in a plastic state, being forced up into channel cavities in the lee of obstructions.

(iv) A combination of the three processes.

He considered that process (iii) was the most likely and this suggestion has been developed in some of the other theories of formation.

The mechanism suggested by Hoppe and Schytt (1953), on the basis of observations in Iceland and Norway, is similar to that of Dyson in that it involves the squeezing of "more or less fluid" debris into hollows formed in the lee of boulders. However, as explained by Schytt (1959), they considered that this process would result in a tapering tail behind the obstruction because ice pressure would soon lower the roof of the cavity. A more complex explanation was therefore offered. They suggested that as the till flows into the cavity the reduction in pressure causes it to freeze to the glacier sole so that it can be carried along by the glacier leaving a new cavity between itself and the boulder. The cavity fills with debris in a plastic state which also freezes solid. The process continues until the distal end of the ridge reaches an area where "the low winter temperature extends through the ice" (p. 224). Here the ridge freezes to the substratum and ceases to move with the ice.

This explanation accounts for the features being parallel to the direction of ice flow, their constant height and considerable length. Boulton (1976a) has suggested that this method of redeposition by freezing to the substratum implies that fluted moraines cannot occur in front of glaciers that are temperate at their snouts. Another objection is that the explanation demands that all the debris in the ridge is supplied from a small area at its head. If the till is in a relatively viscous state it is difficult to envisage a steady supply being maintained. In a more fluid till supply would be easier but the fluid would transmit and equilibrate an applied pressure through itself. Thus the pressure within the material filling the lee-side cavity would be the same as that surrounding it and it would not freeze.

The next major contribution was made by Baranowski (1970). He described features in Spitzbergen emanating from a thermally complex glacier. He considered that the previously suggested formation mechanisms failed to explain the typical regular spacing of fluted moraines as well as the occurrence of ridges in areas lacking large boulders. He suggested that ridges may be initiated by frost heaves in the "ground moraine" under the ice. The material would be forced up into the glacier base at evenly spaced places in a manner analogous to sorted circles and polygons. These mounds would groove the glacier bed and ground moraine would move into the grooves.

This explanation can only apply to a part of a glacier bed down-ice of which the ground moraine is unfrozen, up-ice of which it is frozen and when the "freezing-belt" is itself moving down-ice. Such a situation probably only occurs rarely and even when it does it

would only cause one freezing cycle which would not be sufficient to cause regularly spaced differential heaving.

Paul and Evans (1974) described some flutes formed in deformed fluvioglacial sediments. They presented strong evidence that the flutes were formed by the deformation of unfrozen subglacial material.

Boulton (1976) provided the most recent explanation of formation in a paper based on subglacial observation, detailed clast and matrix fabric analysis and theoretical consideration. He stated that as a major boulder melts out of the basal ice it will be retarded as it ploughs into the till. This will result in a low pressure area immediately in the lee of the boulder and an area of enhanced pressure in the ice around the boulder. Till will move in to fill the low pressure area but when it comes in contact with the ice the pressures will not be in equilibrium and the ice will tend to close the cavity as far as the edge of the area of enhanced ice pressure caused by the boulder. This will result in a tapering till wedge behind the boulder. Beyond this area the ice and till pressure will be in equilibrium, there will be no further tendency for the tunnel to close and a ridge of constant height will result.

He suggested that boulders could be removed from the heads of the ridges by winter readvances at the margin of the glacier or by pressure reduction consequent upon thinning of ice while the boulders were still beneath it. Thus his explanation can be applied to some ridges that no longer have rigid initiating obstructions.

He also pointed out that the apparent regularity of spacing, noted by many workers and of particular importance to Baronowski, is an illusion that can be simulated by drawing parallel lines from

randomly spaced points. The spacing of the lines will tend to cluster around an average value and produce a Gaussian frequency distribution:

"indicating that a clear average spacing is the most likely result of random boulder placement, not an indication of a rhythmic formation process" (p. 307).

Thus the explanation of small-scale fluted moraines offered by Paul and Evans and Boulton can be seen as developments of Dyson's ideas which have been supported and refined in the light of detailed evidence.

Large-scale fluted moraines do not lend themselves so well to detailed analysis both because there tends to be greater uncertainty about the conditions at the time of their formation and because, being larger, comprehensive analysis is less practicable. Thus previous work on these features tends to be descriptive and the proposed mechanisms of formation are speculative.

Gravenor and Meneley (1958), after describing features in Alberta, suggested that material could be entrained in the base of the glacier in high pressure zones from which it would move down-glacier and across into zones of low pressure where deposition could take place. They also cautioned that a full explanation should take account of: (i) the gradation between flutings and drumlins, (ii) the occurrence of flutings in till, stratified drift and bedrock, (iii) the fact that they are long, regularly-spaced features and (iv) the fact that they may result from overriding of existing glacial deposits. In addition to commenting on the gradation between flutings and drumlins they reported that near-by dead-ice hummocky moraine displayed linear trends parallel to the flutings. Such

gradations and relationships have been noticed by several other workers (Prest 1968, Cowan 1968, Aario 1977b).

Shaw and Freschauf (1973) proposed a mechanism involving secondary transverse flow in cylindrical cells of ice near the glacier base, resulting in alternating bands of convergent and divergent ice flow. This would tend to concentrate debris into bands which would melt out to form flutings. They considered that a convergent trend in the orientations of clasts in the sides of flutings merited acceptance of the hypothesis. However the difficulty of interpreting such results can be illustrated by noting that Boulton (1976) interpreted a similar finding as supporting his proposal for the formation of small-scale flutings which involved lateral displacement of the till but no transverse flow of the ice. Shaw and Freschauf offer no other evidence in support of their hypothesis and no driving force for the secondary flow was proposed.

Aario (1977b) suggested a similar scheme in a paper based on a study of the structures of drumlins and flutings in Finland. He presented little evidence but suggested that shear plane orientations indicated ice flow oblique or transverse to the axes of the features during deposition. He therefore suggested the existence of cylindrical flow cells, on either side of the flute, similar to those suggested by Shaw and Freschauf. However Aario's scheme differs from that of the above authors in that each flute was separated from its neighbour by a trough in which faster ice flow parallel to the flutes occurred. Since the features described by Aario are composed of a variety of facies of glacial sediments he considered that formation took place in a series of increments whereas the features investigated by Shaw and Freschauf, composed of only one unit of

till, were thought to have formed in one short event.

Shaw (1980) developed his ideas in the context of a Swiss valley glacier, suggesting that when flow is transversely constricted folding occurs along axes parallel to the direction of flow. He cited steeply-dipping foliation planes and the presence of upstanding medial moraines as evidence of an upward component of ice flow. He suggested that a low pressure area would exist beneath these zones and that fluted^{surfaces} would form below the medial moraines. He did not report the existence of fluted moraines beyond the snout of the glacier but considered lateral moraines to be "half flutings". Unless more concrete evidence in support of these ideas (Aario and Shaw and Freschauf) is presented they must remain speculative.

3.3.3. The importance of Scottish fluted moraines

All fluted moraines in Scotland appear to have been formed by glaciers of the Loch Lomond Advance. They differ from the features described in the above-mentioned papers in several ways. Their scale is different from both of the categories used above since they are generally not more than 4m high and usually less than 500m long but never as small as the small-scale group of features, although some very low broad ridges do occur. They also differ from the small-scale group of features because they do not usually have initiating boulders or bedrock obstructions, although they are sometimes associated with mountain spurs around which ice converged.

They differ from the large-scale group of features because they were formed by an upland glaciation, mainly represented by valley

glaciers, and consequently they occur in areas of relatively high relief. Apart from a small area S of Loch Lomond the Loch Lomond Advance glaciers did not form drumlins; thus the commonly observed association of large flutings and drumlins does not occur.

In Scotland fluted moraines have been used to indicate the former existence of Loch Lomond Advance glaciers by many workers (Sissons eg. 1967 Gray and Brooks 1972, Thompson 1972, Robinson 1977, Ballantyne and Wain-Hobson 1980, Wain-Hobson 1981) and they have been taken to indicate the last directions of ice movement of these glaciers. They have also been useful in reconstructing the form of the glaciers at their maximal extents, implying formation at or near that time.

Fluted moraines have been studied in this project because they are diagnostic subglacial features and the till in them can be compared with that from other features. The previous Section (3.3.2) shows that satisfactory explanations have only been established for small-scale fluted moraines. The Scottish features are an interesting intermediate scale of fluted moraine which, because of the advantages mentioned in Section 3.2, may yield information relevant to the debate about the formation of other features.

3.4. Previous work on hummocky moraines

It is difficult to write a summary of previous work on hummocky moraines because a wide variety of work has contributed to the explanations currently favoured and the term has been applied to a wide variety of features. Thus this section follows the development of ideas for explaining the formation of undulating glacial deposits

and the term hummocky moraine is used to describe such deposits. Since hummocky moraines exhibit little order, detailed measurement and analysis has been rare and description, generalisation and speculation have been dominant in arriving at these explanations.

The features dealt with later in this thesis are composed of bouldery till with a sandy matrix. In some places they are steep sided (up to 38°) and sharp crested, while elsewhere they are less steep, more bouldery and tend to coalesce into ill-defined mounds. In some places they have straight, elongate crests, parallel to one another but elsewhere they appear chaotic. They do not always represent a particularly large accumulation of till; for instance some of the most impressive features (Chapter 7) are separated by areas of thin till so that if the material was evenly spread it would produce a till sheet 2-3m deep. Many of the features dealt with in the papers mentioned below are not at all similar to these moraines but they are relevant because the explanations proposed for them have been broadened into general models of hummocky moraine formation.

The first major study of hummocky moraines was made by Hoppe (1952). He reported that earlier workers such as Tanner (1914) and Mannerfelt (1945) had used the term dead-ice moraine because they believed that pointed ridges and hillocks must have been formed by material lowered from the surface of disintegrating, stagnant ice. Hoppe summarised opinion at that time as being that:

"The positive forms of dead-ice moraine originated as fillings of crevasses in the ice. The material fell into the crevasses from a thick covering on the surface of the glacier" (p. 3).

He pointed out that the Swedish literature had been influenced by observations of the formation of irregular hummocky moraines as a result of such a process occurring on small Alaskan valley glaciers

(Tarr and Martin 1914). He considered that the ablation moraine on these glaciers was composed of material that had fallen onto the ice from the valley sides and that the situation could not be applied to the Swedish ice-sheet which would have had no such sources of debris. The evidence presented in Hoppe's paper consists of detailed maps and descriptions of a large variety of features and the results of clast orientation analysis from some of them. Clast orientations transverse to ridge crests, together with the high compaction and unwashed state of the till and the presence of meltwater channels cutting the features, led Hoppe to conclude that many of the features were formed subglacially by squeezing of unfrozen material into basal cavities. Where regular patterns occurred he attributed them to the pattern of ice break-up prior to stagnation. In spite of the evidence provided by Hoppe, and his objections to the majority view, that view (quoted above) has been developed, refined and applied to the majority of hummocky moraine landscapes.

Gravenor (1955) described large (100m diameter), subdued (4.5m average height) prairie mounds composed mainly of till with some stratified material. He envisaged areal stagnation and down-wasting of the ice with debris collecting in pits on its surface but he did not provide an explanation for the presence of the debris at a high level in the ice.

Gravenor and Kupsch (1959) adopted a similar explanation for fields of ridges and mounds in western Canada. They termed the features "disintegration moraines" and made a distinction between uncontrolled and controlled disintegration moraine, the latter showing patterns, such as ridges aligned parallel or at right-angles

to one another, which had been inherited from the pattern of weaknesses in the ice. They criticised Hoppe's evidence for subglacial squeezing, suggesting that clast orientations transverse to ridge crests could be attributed to post-depositional, down-slope movement of material. However they did attribute some of their features to formation at the base of stagnant ice. They also asserted that there were several methods by which basal debris could reach a high level in the ice. They specified two of these: one involved the readvance of active ice over stagnant ice which would result in the basal debris of the advancing ice moving into an englacial position, the second was through the development of thrust planes along which debris could be elevated.

The idea that thrust planes or shear planes could raise material from the glacier base to high levels in the ice stems from the observations of Goldthwait (1951). He reported large numbers of narrow (0.25 to 25mm) bands of dirt cropping out near the margin of the Barnes Ice-cap and dipping steeply up-ice. Most of these bands cropped out within 100m of the snout of the glacier and the debris flowed down the frontal slope to produce moraine ridges.

Bishop (1957) reported a similar situation at Thule in Greenland and attributed the shear planes to differential movement between the active glacier abutting against stagnant ice at its snout. Weertman saw two major problems with this idea: (i) the method of incorporation of debris into the glacier base and (ii) the presence of so many shear planes so close to one another. He suggested that under a glacier that was cold based at its margin, but warm based farther up-ice, meltwater and debris would freeze to the

base of the ice in layers as it entered the cold-based area. Therefore many of the debris bands would not represent shear planes. Lliboutry (1964-65) suggested that the process of regelation (freezing of meltwater to the glacier base in the low pressure area down-ice of a bedrock obstruction) could account for the incorporation of basal debris. More recently Hooke (1973) has attributed the elevation of the dirt-bands to the glacier overriding non-glacial ice that had accumulated at its margin but he did not deal with the initial problem of entrainment of the debris into the base of the glacier.

Another major idea in the development of this type of explanation was contributed by Clayton (1964). He described the debris on the surface of Alaskan glaciers and stated that:

"most of the ablation till originated by the concentration of subglacial debris that has been carried up into the glacier along imbricate thrust planes when the active ice was thrust up over less active or stagnant ice" (p. 108).

However his most important contribution was to suggest an analogy between an area of stagnant ice protected from surface melting by ablation till and therefore melted by water flowing within it and karstic limestone dissolved by flowing water. The idea of thermo-karst was later used by Parizek (1969) to explain a variety of mounds, ridges and plateaux described by Hoppe (1952) and Gravenor and Kupsch (1959). He also demonstrated diagrammatically that an almost unlimited range of features could be produced by areal melting of debris-covered, stagnant ice and inversions of relief as ice cores disappeared.

During this period several other writers, describing different hummocky moraine landscapes, drew on some or all of the following

interrelated ideas. (i) Debris elevated to the glacier surface by thrust planes. (ii) Areal ice-sheet stagnation. (iii) Slow, patchy melting of ice with debris concentrated into depressions. (iv) Relief inversions to produce hummocks and ridges as the ice remnants disappeared. (e.g. Hartshorn 1958, Niewiarowski 1963, Hughes 1964, Reid 1969, Bartkowski 1969, Okko and Perttunen 1971, Daniel 1972).

In a series of five influential papers Boulton (1967, 1968, 1970a, 1970b and 1971) gave detailed evidence and descriptions of the processes of debris entrainment, transport and deposition occurring on some Spitzbergen glaciers. From his observations he went on to make generalisations (Boulton 1972) and to propose a glacial landform classification (Boulton 1976b, Boulton and Paul 1976, Boulton and Eyles 1979).

In the first five of the above-mentioned papers he described areas of stagnant ice containing many debris bands, up to 5m thick in the ablation areas of several glaciers. This debris was released onto the surface of the ice, retarded further melting, and was gradually lowered to the ground. He showed that complex stratigraphic relationships of till and waterlain sediments are produced in such an area and he used the term flow till for till which moved across the surface of the ice before being deposited. The debris on the ice surface was unevenly distributed and, on deposition, produced a hummocky terrain. His examples demonstrated that a large area of hummocky moraine topography can be produced by the gradual melting of successive narrow bands of stagnant ice at the edge of an actively retreating glacier and therefore does not imply areal stagnation of the glacier.

He also addressed himself to the problem of entrainment of englacial debris (Boulton 1970b). He considered that thrusting was not important to initial entrainment since the debris bands were parallel to the foliation planes in the ice and both were cut by thrust planes. He concluded that the regelation process suggested by Lliboutry (op. cit.) was more important than Weertman's suggestion (op. cit.). In addition he proposed that the Spitzbergen glaciers were of a sub-polar type in which more water was frozen to the glacier base by regelation than was released by pressure melting, the necessary water being supplied from a warm based area farther up-ice. Thus he suggested that debris could be raised to progressively higher levels in the ice. In contrast, under temperate glaciers there is no net gain by freezing and debris cannot rise above a shallow basal band. He also envisaged entrainment by plucking of blocks in areas where a thin layer of the glacier bed became frozen to the base of the ice. In a retreating glacier longitudinally compressive flow would result in folding and thrusting in the ice which would elevate the debris entrained by the above processes to higher levels.

At the end of the paper Boulton (1970b, p.227) suggested the generalisation that:

"many polar and sub-polar glaciers... carry very considerable amounts of englacial debris from the glacier bed, whereas temperate glaciers... carry very little basally-derived englacial debris"

This statement was immediately and directly challenged by Andrews (1971, 1972) who cited counter-examples in Baffin Island and elsewhere.

In "Modern Arctic glaciers as depositional models for former ice-sheets" (1972) Boulton summarised the results of his observations in Spitzbergen and proposed a classification system for the sediments

produced. He suggested that many problems in glacial geology have been caused by the lack of an adequate modern analogue (cf. Garwood 1913, "Arctic glaciers and British ice-sheets"). For instance, the assumption that all fine-grained tills are subglacial lodgement tills has caused difficulties, especially where two such layers are separated by stratified deposits. From this and other examples that he gave it is clear that deposition by processes occurring in Spitzbergen provides improvements on previously held explanations.

In an example of direct relevance to this chapter he stated that:

"There has.. been a recent tendency to ascribe many constructional, ridged and hummocky till forms to subglacial formation. Although this is undoubtably correct for many forms such as drumlins and fluted moraines, it is a very questionable procedure in the case of all mounds and ridges of till which do not have such regular distributions. For instance... many of the types of hummocky moraines described by Hoppe (1952) from Norrbotten in Sweden and attributed to hypothetical subglacial processes, for which there are as yet no modern analogues, are identical to moraines which form supraglacially at the margins of actual glaciers in Spitzbergen" (p. 384).

In this case it is pertinent to comment that supraglacial processes are more easily observed than subglacial processes and it is therefore more difficult to find modern analogues for the latter.

Clapperton (1975), having observed surging glaciers in Spitzbergen and Iceland, noted that surging was a common characteristic of Spitzbergen glaciers (cf. Leistol 1969). He suggested that the englacial debris characteristics described by Boulton were attributable to surge behaviour and could occur in both sub-polar and temperate glaciers. He pointed out that a surge would increase lee-side cavitation and make a large volume of water available for regelation and that complex folding and thrusting would

be produced by compressional flow at the snout.

Boulton subsequently expanded the genetic classification of tills based on the contrasts in load derivation and transport position (Boulton 1976, Boulton and Paul 1976). Two main sources of glacial debris were distinguished: these were the glacier bed and the valley sides overlooking the glacier. The latter source is only important in valley glaciers and is dealt with in more detail in a later paper (Boulton and Eyles 1979). The former source is said to give rise to two types of deposit which are important in all glaciers. The first, the subglacial sediment association and land system, formed of lodgement till and characterised by smooth till sheets and ice-moulded landforms occurs where the englacial load was thin and has not masked the lodgement till. This is the dominant mode of till deposition from temperate glaciers. The second, the supraglacial sediment association and land system, formed of flow till and melt-out till with outwash products and characterised by undulating ice-stagnation remnants, occurs where polar or sub-polar glaciers deposit large englacial loads in the manner described by Boulton in Spitzbergen. Boulton (1976, p.71) stated that:

"This supraglacial sediment association seems typical of much of the terrain of the last glaciation in the U.S.A., north Germany and Poland and I would suggest that it forms the great bulk of undulating stagnation topography".

The classification was completed by the description of a glaciated valley sediment and landform association which can be superimposed on either of the other two systems (Boulton and Eyles 1979, Eyles 1979). These authors described how supraglacial debris derived from the valley sides and nunataks overlooking the glacier is deposited to provide a variety of landscapes depending on the volume

of debris and the speed of retreat or advance of the glacier. A small volume of debris deposited from a slowly retreating glacier can produce dump cones; if retreat is faster a "coarse-textured carpet of till" (p. 14) results. If a large volume of supraglacial debris is present melting is retarded, stagnation occurs and the ice melts chaotically producing thaw-lakes and kettle holes among a hummocky till complex.

Boulton's descriptions of glacial processes in Spitzbergen have proved to be a very useful model for explaining Pleistocene glacial landscapes (e.g. Aarolahati 1974, 1975; Clayton and Moran 1974, Karczewski 1975; Minell 1977a; Kurimo 1977). Rains and Shaw (1981) have reported similar depositional environments on polar glaciers in Antarctica. Boulton has made use of his own scheme in interpreting patterns of glacial deposition in part of Wales (Boulton 1977) and for Britain as a whole (Boulton et al. 1977). In the latter paper a general map shows areas of drumlins and supraglacial deposits, the latter being defined as having hummocky morainic and kamiform topography reflecting deposition on and between stagnating ice masses.

Boulton et al. stated that:

"a similar association is also produced in valley glaciers where medial and lateral moraines form englacial debris sequences. Much of the supraglacial sediment (shown on the map) in highland Britain has this origin" (p. 242).

Two of the largest areas of supraglacial sediments on the map occur in N Cumbria and in the Tees valley, areas where other general maps e.g. Embleton and King (1975) show drumlins, indicating that very subdued landforms can indicate deposition from a supraglacial position.

The foregoing sequence of papers illustrates the development of the dominant mode of explanation of hummocky moraine landscapes. However these ideas have not been all-embracing and a considerable number of examples have been explained as being formed subglacially by active or stagnant ice. Squeezing of debris into crevasses and cavities at the base of stagnant ice has been suggested as the main process producing features described by Hoppe (1952, 1957), Stalker (1960, 1973) and Henderson (1972), while Gravenor and Kupsch (1959), Parizek (1969) and Aarolahati (1974) have envisaged this as a subsidiary process adding to the effects of deposition from the ice surface.

The suggestion that hummocky landforms have been produced subglacially by active ice has generally been limited to Rogen or "ribbed" moraines, although Hirvas (1977) considered that extensive hummocky moraines in Finland had been produced during the expansion of the last ice-sheet. Cornish (1980) gave a review of the literature concerned with Rogen moraines (ridges transverse to former ice flow). In this field there has been a progression of ideas from an initial opinion that the features were marginal moraines (e.g. Högbon 1920), through suggestions of deposition from the surface of dead ice (Lundquist, G 1937) and squeezing into basal crevasses in stagnant (Hoppe 1952) and active (Lundquist, J 1969) ice, to a strong consensus among modern workers that the features were formed at the base of active ice: (Aario et al. 1974; Sugden and John 1976; Aario 1977b, 1977c; Shilts 1977; Carl 1978; Shaw 1979; Cornish 1980; Markgren and Lassila 1980). Of these authors Aario and Markgren and Lassila identified a gradation from Rogen moraines to shorter hummocky features. It is clear that the main impediment to an

earlier adoption of this explanation was the problem of envisaging the survival of transverse ridges under active ice flow.

Throughout the period considered in this chapter there have been important theoretical developments regarding ice deformation and glacier sliding processes carried out by workers such as Boulton, Glen, Lliboutry, Nye and Weertman (see Paterson 1981). In dealing with the complex relationship between glacier ice and its bed (rough or smooth) the analysts have usually disregarded the possible effects of intervening, unconsolidated debris. Boulton's assertion that temperate glaciers have little basal load, together with observations, from subglacial cavities, of glaciers flowing over bedrock (Kamb and La Chappelle 1964, Peterson 1970 and Vivian and Bouquet 1973) tended to justify this assumption. Recent findings by Engelhardt et al. (1978) have, however, changed this position. They took photographs at the bottom of boreholes drilled into the Blue Glacier, Washington. They found that the glacier contained a large englacial load near its base and had a thin (10cm) layer of "active subsole drift" (p. 505) between the glacier and its bed which provided a "ball-bearing" (p.505) mechanism for basal sliding. They also found suprisingly low basal sliding velocities and went on to suggest that earlier observations, in subglacial cavities, of high basal slip velocities were:

"atypical because they occur in abnormal situations where there is extensive ice separation from the bed (basal cavitation) and where basal debris is relatively scarce or absent." (p.504).

3.4.2 The importance of Scottish hummocky moraines

Hummocky moraines are common features in many upland valleys in Scotland. They, together with end moraines, were:

"cited as proof of the former existence of glaciers in Scotland by the early exponents of the glacial theory in the 1840s, and during subsequent years of the last century it came to be accepted by all Scottish workers that a stage of valley glaciation succeeded the great mer de glace" (Sissons 1967, p.139).

Charlesworth (1955) used these features to delimit and provide a name for his Moraine Stage of glaciation. He also described the composition of the mounds as being:

"loose, unsorted debris, the stones being angular or sub-angular, mixed indiscriminately and of all sizes".

Sissons (1967) described the features and discussed their origin.

"Many of the mounds are no more than 20 or 30 feet high but some attain heights of more than 100ft... The surfaces of the mounds are often littered with angular boulders and similar boulders are plentiful in the mounds themselves... The boulders are usually mixed with an assortment of stones of all sizes as well as with finer material. This debris is mostly ablation till and was deposited by valley and corrie glaciers, often during the final phase of the last glaciation." (p.95).

"In many... valleys the moraines appear to form a sea of chaotic mounds lacking any systematic arrangement. It may be that in some valleys there is in fact little pattern, the deposits representing the debris let down onto the ground as the glaciers finally decayed, probably associated with considerable redistribution of the material by meltwater streams. In other instances knobbly bedrock outcrops appear to have exerted a considerable control on the distribution of the morainic material, for locally many of the mounds may be seen to have a core of solid rock." (p.97).

He went on to describe lines and patterns of mounds that also occur, especially V-shaped, cross-valley arrangements. He concluded that these features:

"suggest the possibility of subglacial accumulation in relation to crevasse systems in the ice at a time when the ice had become

stagnant." (p.97).

Subsequently Sissons and many other workers have used hummocky moraines to delimit former Loch Lomond Advance glaciers (Gray and Brooks 1972; Sissons 1972, 1974a, 1977a, 1977b, 1979c; Sissons and Grant 1972; Thompson 1972; Sissons et al. 1973; Robinson 1977; Ballantyne and Wain-Hobson 1980; Cornish 1981; Wain-Hobson 1981; Thorp 1981). The justification for this practice has been that hummocky moraines of fresh appearance often occur immediately up-valley of end moraines. In other valleys hummocky moraines end abruptly and may be succeeded down-valley by outwash deposits. In the absence of an end moraine the limit of hummocky moraine is interpreted as the most likely glacial limit.

Sugden (1970) described hummocky landforms in the valley floors in the Cairngorms. He noted that among the features there were ridges, running down the line of maximum slope of the valley side. The material forming the features "almost invariably" has a sandy matrix and some bedding occurs. He concluded that

"The ridges comprising the "hummocky moraine" in the Cairngorms appear to have been deposited subglacially by meltwater as eskers." (p.208)

and that:

"its general distribution, form and composition suggest that it is characteristic of fluvioglacial deposition within ice that stagnated in the floors of individual glens" (p.209).

He related this occurrence to the last stage of ice-sheet deglaciation when the mountain ridges cut the ice off from its source of supply. Sissons (1974b) asserted that there was a pronounced contrast between hummocky moraines and the "massive fluvioglacial accumulations associated with ice decay" (p.317).

Most other workers have reported unsorted bouldery debris in most exposures of hummocky moraines and evidence of bedding in some others. A sandy matrix has been an almost constant feature of the deposits.

Subsequent to the above debate Clapperton et al. (1975) found a full Lateglacial stratigraphy in an area of fluvioglacial mounds at Loch Builg in

the eastern Cairngorms, showing that those features predated the Loch Lomond Advance. Clapperton and Sugden (1977) have reinterpreted the "hummocky moraines" of the SE Grampians, taking account of sudden down-valley terminations of the features succeeded by terrace suites, to conclude that:

"the characteristics of hummocky moraine imply an origin closely linked with short tongues of glacier ice that stagnated and wasted away in situ" (p. 7).

Finally, after Sissons (1979c) mapped former Loch Lomond Advance glaciers in the Cairngorms, Sugden (1980) insisted that "the main point at issue is the origin of the hummocky moraine" (p. 18).

In the light of the models of glacier sedimentation described in the previous section, the above descriptions and the illustrations in the literature (Wright 1937, Plate x; Sissons 1967 Plate x,b and xi,b; Sugden 1970, Fig.5) it would seem likely that Scottish hummocky moraines are part of a glaciated valley sediment association or a supraglacial sediment association. In most of the detailed maps published by the authors listed above hummocky moraines and fluted moraines have been given separate symbols, a practice tending to imply a contrast between subglacial fluted moraines and supraglacially-deposited hummocky moraines. However most extended descriptions show some evidence to counter this impression.

Sissons (1967), in the section quoted above, noted bedrock control which suggests subglacial accumulation. Thompson (1972) noted a similar situation on the Rannoch Moor, where bedrock knobs occur at the stoss end of some of the features. Gray and Brooks (1972) described a "lineation of hummocks" (p.99) at two locations on Mull and their plate caption includes the phrase "the fluted moraine consists of lineated hummocky moraines". Robinson (1977), in describing a valley in the Torridon area (dealt with later in this thesis (Chapter 6)) referred to fluting superimposed on hummocky moraine ridges. In another valley (dealt with in Chapter 7) she considered that some of the steep-sided and sharp-crested features "may be an abbreviated form of flutings" (p.72). Sissons (1977a) described fluted moraines superimposed on dead-ice topography with a relief amplitude of 25m in Strath Dionard. He proposed that active ice overrode dead ice in this area and described a similar situation in Loch Skene Coire in the Southern Uplands. This explanation is also invoked by Robinson in the first of the examples quoted above. Wain-Hobson (1981) refers, on several occasions, to relationships between fluted and hummocky moraines e.g.

"some of the fluted moraines then become fragmentary and form elongated hummocks" (p. 40, cf. p. 30 and p. 31).

Lawson (pers.comm.) notes an association between the extent of coarse-grained rock-types and the occurrence of hummocky moraines in Assynt, implying that the debris has been subglacially derived.

The conflicting interpretations described in this chapter may indicate that there is a variety of features of different origins that have been called hummocky moraines. However the suggestions that some of the features do not conform to the most likely model of

formation, the importance that has been attached to their origin and the use that has been made of them in geomorphic mapping make a detailed study of Scottish hummocky moraines essential.

CHAPTER 4.
TECHNIQUES AND PROCEDURES

4.1 Introduction

The techniques used in this project were chosen with respect to the following three considerations.

1. Their relevance to the solution of the problems posed.
2. The limitations imposed on one worker using manual methods in remote country.
3. Their comparability: the procedures had to be applicable to all the environments sampled and the results had to be summarised to allow comparison between different samples or groups of samples for a variety of tests.

This chapter describes the procedures and techniques employed in order to facilitate the reader's assessment and understanding of the following chapters. Most of the data were gathered from pits and these are dealt with first. Each of the techniques, from the field to presentation, is then dealt with separately.

4.2 Sample pits

The most important sources of data were pits dug in the moraines. The pits were normally sited on the crests of features because peat development and pedogenesis were least in these positions and because the material there was least likely to have been altered by post-depositional slope processes. In some areas

pits were also dug in the depressions between features (swales). Most of the pits were c. 1m deep and they usually displayed the following, podsol-type, soil profile (Plate 4.1). A dark humus layer 5-10 cm deep, sometimes overlain by peat, was underlain by a sandy, leached horizon of a pale yellow colour, darkening to an orange iron-pan and, sometimes, a black manganese concentration at a depth of less than 0.5 m. Below this the material was pink or yellow in colour and displayed no further alteration with depth. Most of the large till samples were taken from near the bases of the pits, and therefore below the iron pan, to eliminate the effects of iron staining and concretion and to minimise the effects of eluviation. Other till samples were taken from higher in the profiles for comparison. Each pit was dug to its full depth before the sample was extracted from the side of the hole (the overburden having been removed). This minimised contamination by debris falling from higher levels and reduced the danger of particles being crushed during extraction.

4.3 Particle-size analysis

The material to be sampled was usually a diamicton with a large proportion of coarse gravel including cobbles. It was therefore considered important that particle-size analysis include the coarse material. This demanded that large samples should be taken since the presence or absence of one particle of coarse gravel would greatly alter the measured particle-size distribution of a small sample. Pessega (1957) suggested that the mass of a sample should be 100

0.7m. The pit was 1.5m deep and 1.5m wide. The water level was 0.5m.

Plate 4.1 A sample pit
A typical sandy till with angular clasts and slight iron staining in the upper 0.5m.

The pit was 1.5m deep and 1.5m wide. The water level was 0.5m.



times greater than the mass of the largest particle in the sample. This can only be a guideline since long clasts passing through any chosen mesh size can have a very great mass. Driemanis and Vagners (1971a) used samples of 1m^3 and included samples up to -8 ϕ , Slatt(1971) used samples of 5-10kg for particles up to -5.25 ϕ , Johanssen (1972) used samples of 106kg for particles up to 200mm diameter, Mills (1977a) used samples of 50kg for particles ou to -6.67 ϕ and Haldorsen (1981) used 5kg samples for particles up to -5 ϕ . In the light of this information the writer decided to take a 25kg sample for particles up to -6 ϕ (64mm) diameter. Since a large range of diameters was being included 1 ϕ screen intervals were used.

Each sample was weighed in the field on a spring balance in 5 or 6 portions of c. 5kg, each part being weighed to the nearest 25g. The sample was passed through four screens in the field (-6, -5, -4 and -3 ϕ) and the resulting three coarse fractions were weighed on the spring balance. Most of the material finer than -3 ϕ was discarded but a subsample of 1.5-2kg was weighed and retained. The importance of sampling the coarse fraction of the sediment is illustrated by the fact that 42.1% of all the material sampled fell into these three size-fractions.

In the laboratory this subsample was air dried and reweighed to find the moisture content of the subsample at the time of sampling. Knowing this it was possible to estimate the moisture content of the fine material in the whole (25kg) sample and, hence, to work out a corrected dry weight for the whole sample. When this had been done the weights of the three coarse fractions could be expressed as percentages of the whole sample. No correction was made for the moisture associated with the gravel coarser than -3 ϕ because the

surface area of this material is small compared to its mass.

After being air-dried and weighed each 1.5-2kg subsample was lightly broken up using a rubber bung. The -3 to -2 ϕ and -2 to -1 ϕ fractions were separated by hand sieving and then weighed. The subsample was a known proportion of the mass of the whole sample and by multiplying the masses of these two fractions by this proportion their masses in the whole sample were determined.

The residue (finer than -1 ϕ) was coned and quartered until only c. 100g remained. This was shaken for 15 minutes through a column of sieves down to 4 ϕ on a mechanical shaker incorporating both rotary and tapping motions. The fractions from fifteen of the samples were examined under a microscope after sieving and it was found that aggregate particles were very scarce. Each of the fractions was weighed on a torsion balance and the percentage of the whole sample falling in each fraction was determined in a manner similar to that described above but with a second multiplication factor to take account of the second subdivision of the sample. Some of the sieve columns were reassembled and shaken for another 5 minutes, reweighed, shaken for a further 5 minutes and reweighed again to see whether additional shaking allowed more material to pass through the sieves. In all cases the changes in the recorded weights after these additional periods were insignificant.

For each sample a further subsample (c. 15g) of the material finer than 4 ϕ was dispersed in sodium hetametaphosphate and pipette analysis was carried out over 8-9 hours to find the contributions of fractions down to 9 ϕ diameter. In view of the precautions mentioned above it is thought that the results of the sieving are accurate.

However the almost complete absence of fine silt recorded in some of the samples may be attributable to the problems inherent in sedimentation analysis. It was not possible to ensure a steady temperature throughout the day, fluctuations being up to 5°C, thus some convection circulation may have taken place. Secondly the samples were not composed purely of spherical quartz particles (cf. Curray and Griffiths 1955). Both these factors would have retarded settling rates and may therefore help to explain the near absence of fine silt and the comparatively large percentage of material still in suspension at the end of the sampling period. The apparent shortcomings of the pipette analysis are made less important by the fact that only 8.5% of the material sampled was finer than 4 ϕ .

For graphical presentation these results were plotted in two forms: cumulative-percentage frequency curves and percentage frequency histograms. The former allows comparison of groups of samples on the same diagram and the latter is an easily-read, illustrative method which can incorporate lithological data.

The numerical presentation of the results is a more difficult problem. Several groups of measurements have been presented that compare the particle-size distribution, sometimes after certain transformations, to a normal distribution and assess its degree of central tendency (Inman 1952, Folk and Ward 1957, McCammon 1962). Reservations have been expressed about the suitability of applying these measures to samples that do not show any central tendency and that differ greatly from normality (Griffiths 1967, Buller and McManus 1979).

In a study where several characteristics of the sediment have been measured and are being compared it is also preferable to

summarise each piece of information, if possible, as one value to simplify statistical comparison.

With these two points in mind the percentage frequency histograms were studied. It was clear that most of the samples had a bimodal distribution. Only four of the seventy-eight samples were unimodal, eleven had three modes and one had four modes. The last-mentioned sample is illustrated in Fig. 4.1 and it can be seen that two of the modes are reversals of falling trends. An underlying bimodal shape is still present as it is in all those distributions that have three modes. Thus in each of these cases only the larger of a closely-related pair of modes was considered in the following catalogue.

51 modes occurred in the -6 to -5 ϕ column

21	"	"	"	"	-5 to -4 ϕ	"
3	"	"	"	"	-4 to -3 ϕ	"
3	"	"	"	"	-3 to -2 ϕ	"
23	"	"	"	"	1 to 2 ϕ	"
45	"	"	"	"	2 to 3 ϕ	"
6	"	"	"	"	3 to 4 ϕ	"

All but one of the intervening troughs occurred in the -1 to 0 ϕ and 0 to 1 ϕ columns. The mean percentages of these columns are 4.92 and 4.73 respectively and they have standard deviations of 1.03% and 0.85% respectively.

The figures show that two modes are almost always present and that the modes occur in the same parts of the distribution in almost all cases, one mode being in the gravel fraction between -6 and -4 ϕ and the other being in the sand fraction between 1 and 3 ϕ . In

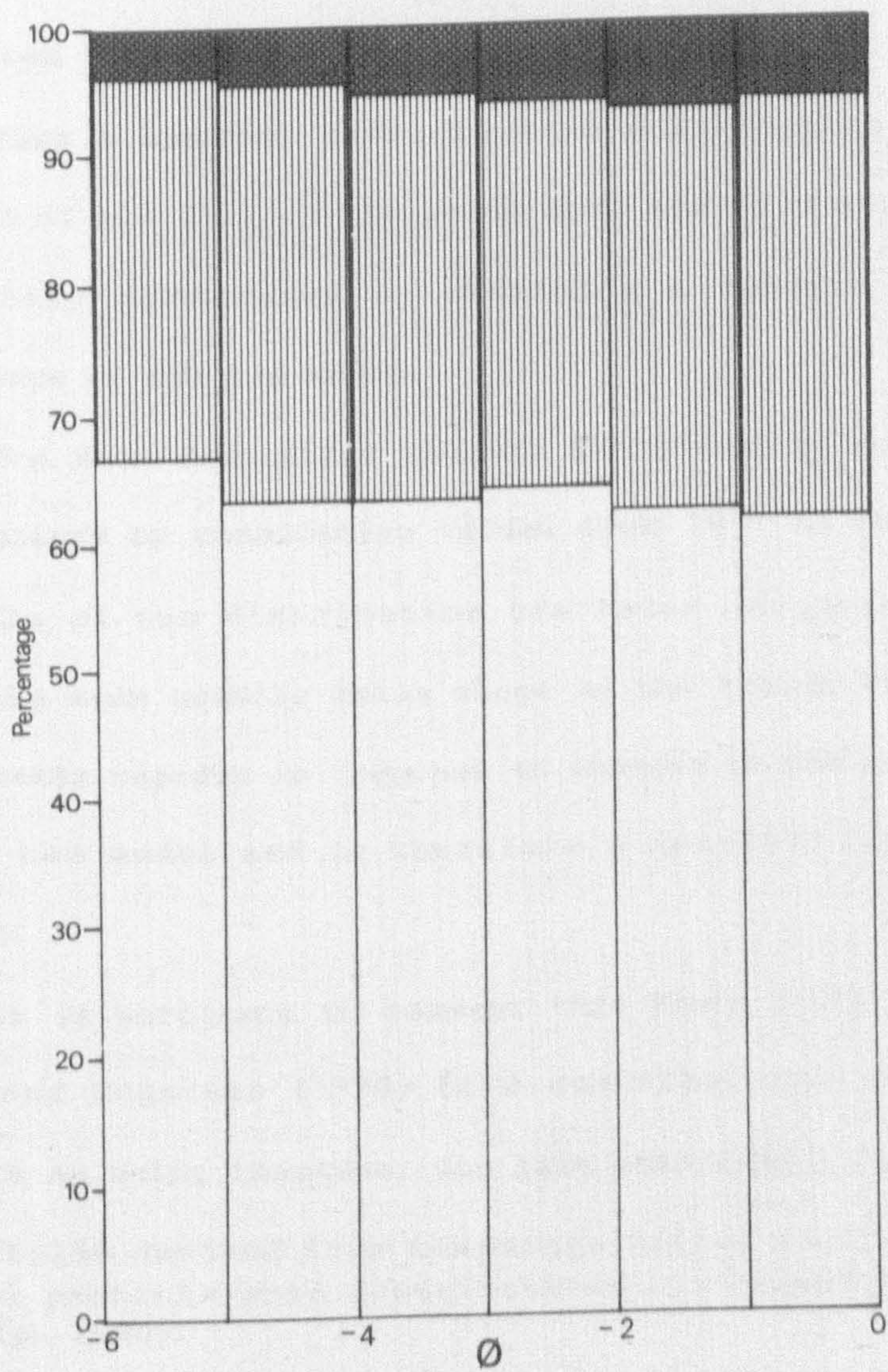
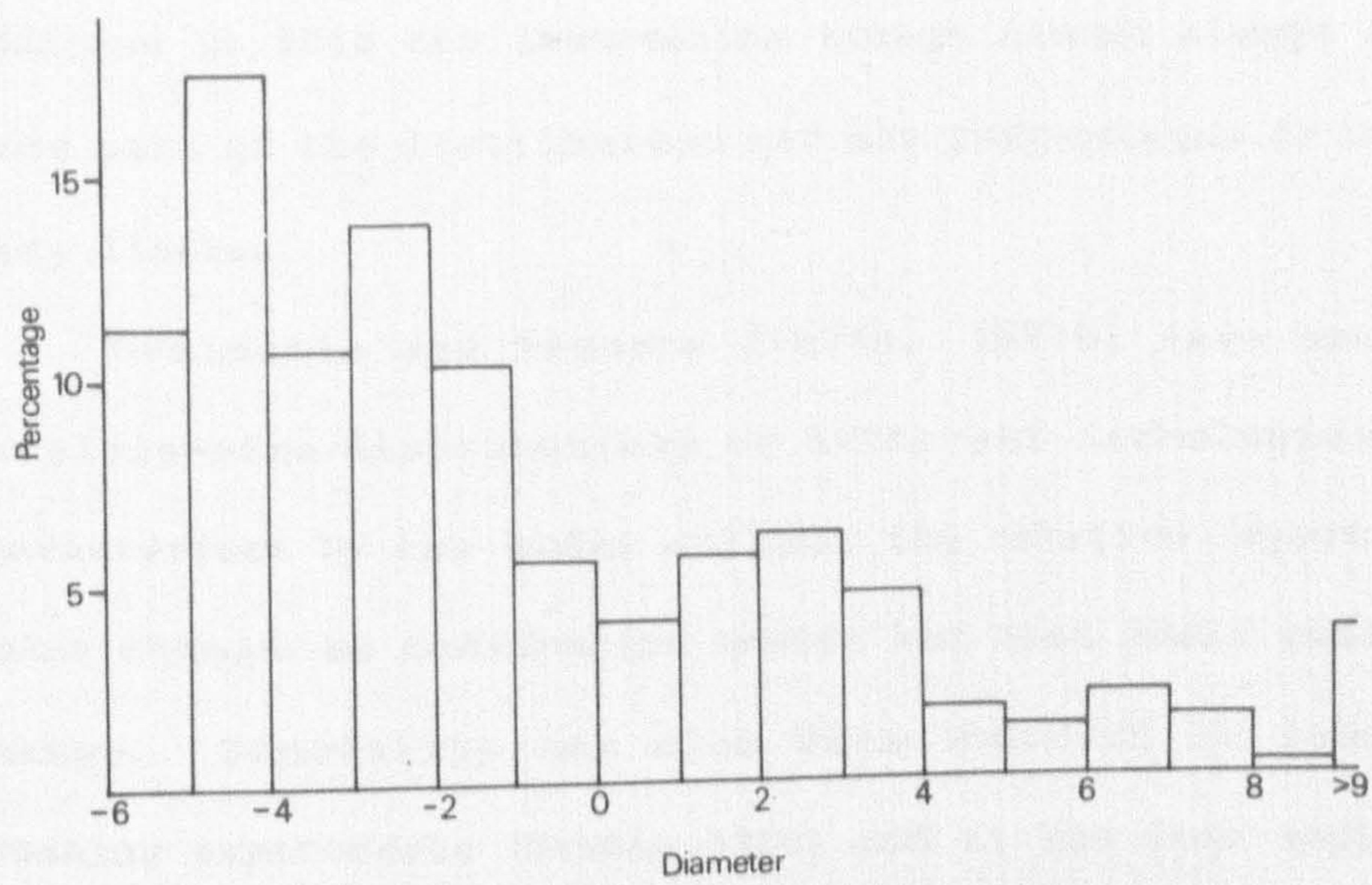


Fig.4.1 Particle-size histogram

This graph shows the particle-size distribution of the sample that had four modes and illustrates that even in this case the gross form of the distribution is bimodal.

Fig. 4.2 Rock-type proportions from all the samples in the project

The dark shading represents ice-sheet erratics, the vertical stripes represent quartzite and the blank areas represent sandstone.



addition to this the intervening trough almost always occurs in the same part of the distribution and the percentages in these columns vary little.

Dreimanis and Vagners (1971a, 1971b) have shown that the particle-size distributions of different lithologies in till are characterised by two modes and that the relative importance of these modes changes as comminution occurs but that their positions do not change. Bimodality has also been observed in laboratory rock crushing experiments (Gaudin 1926) and it has been explained as the result of easy crushing of rock fragments down to the relatively stable mineral grains that constitute the second mode (Beaumont 1971, Haldorsen 1981).

Thus a bimodal particle-size distribution is an important feature of the till of the study area and this distribution can be adequately summarised by obtaining a measure of the relative importance of the two modes.

The Mean Percentile measure as defined by McCammon (1962) was used because by considering values from 10th to the 90th percentile the ends of the distribution are taken adequately into account. Since the mean usually falls close to the trough in the distribution it migrates rapidly in response to changes in the relative importance of the two modes and is therefore a sensitive indicator of these changes.

It is pertinent to comment that Slatt (1972), Eyles (1978) and Eyles and Rogerson (1978) have described till formed by valley glaciers as being immature, the last mentioned authors stating that:

"tills derived from temperate valley glaciers do not reveal bimodal particle-size distributions, irrespective of source rock type" (p. 1690).

Eyles (1978) has criticised the methods of Mills who has consistently found a bimodal distribution in valley glacier tills from a variety of locations (1977a, 1977b and 1978). Eyles considered that these results stemmed from the change from sieving to sedimentation analysis at 4 ϕ , implying that aggregate particles had been retained in the finer sieves. The precautions taken in this project were undertaken with this debate in mind and the results summarised above add to those of Mills in showing that Eyles's and Rogerson's quoted assertion is an overgeneralisation.

4.4 Lithological analysis

As mentioned in the previous chapter determination of the proportions of sandstone, quartzite and those other rock types (Lewisian Gneiss, Moine Schist and Furoid Beds from the Cambrian sequence) that could only have been brought into the area by major glacial activity predating the Loch Lomond Advance (and therefore termed ice-sheet erratics) was an important part of the project. Two types of lithological analysis were undertaken to measure the proportions of different rock types.

The first was carried out on the material of the main samples for each of the 1 ϕ fractions from -6 to 0 ϕ . The three coarsest fractions were processed in the field by weighing each of the different components of the -6 to -5 ϕ and -5 to -4 ϕ fractions and by counting the proportions in a subsample of 200 to 300 stones taken from the -4 to -3 ϕ fraction. In the laboratory a similar subsample of each of the fractions between -3 and 0 ϕ was counted, a binocular

microscope being used for the two finest fractions. In the fractions finer than 0 ϕ a large proportion of the particles were individual mineral grains. Many quartz grains were derived from the sandstone and although some of these have a red cement stain and others have faceted surfaces, it was not possible to differentiate all of them from grains of Cambrian Quartzite (J. Lovell pers. comm.). It was therefore not possible to ascertain the proportions of different rock-types for fractions finer than 0 ϕ .

Fig. 4.2 shows the proportions of each of the rock-type classes for each fraction for all the 72 samples in the project. If there were any tendency for the different rock-types to favour different size fractions this graph would have recorded it but, apart from a possible tendency for ice-sheet erratics to favour the finer fractions at the expense of the sandstone, the proportions vary little. This indicates that the rock-type proportions of a particular size fraction are representative of the rock-type proportions of the till.

The second mode of lithological analysis made use of this result and simply consisted of taking a sample of 200 to 300 pebbles of the -4 to -3 ϕ fraction. This method had the advantage of being quick and, because it needed a far smaller sample volume could be used to search for small scale variations. It was used in several ways.

1. Sampling at very small vertical intervals (10 to 15cm) within pits determined how well the main sample represented the material over the full depth of the pit and whether there was any significant change in the lithological composition of the material over that range of depth.

2. In some places, where less comprehensive information was required or remoteness restricted the amount of work that could be undertaken, samples of this kind were used on their own to indicate how the lithological composition of a till changed in response to changes in bedrock lithology.

3. In some natural sections samples at 1m vertical intervals were used to determine the degree of change in lithological composition over greater depth ranges.

4.5 Stone shape

The main purposes of collecting shape data were to differentiate debris that had been fragmented by subaerial agencies (mainly frost action) from debris that had suffered abrasion and crushing at the base of the glacier and, within this second group, to assess the degree of wear of the clasts. The first of these purposes was served by studying the form or axial ratios of the clasts and the second was served by studying their roundness (sensu Barratt 1980).

4.5.1 Clast form

The long (a), intermediate (b) and short (c) axes of 25 clasts of each of the important lithologies were measured at each site. Gaps in the data reflect changes in what was considered an "important" component of the till.

Ballantyne (in press) has suggested that, since mechanical comminution will tend to break clasts across their longest axis, this

being the direction in which the greatest moment can be achieved, the result will tend to be a reduction in the proportion of elongate clasts and an increase in blockiness. He has shown that the simplest measure for discriminating blades and plates from blocks is the c/a ratio (Sneed and Folk 1958) and has demonstrated this in differentiating clasts from glacial and periglacial environments.

In this study the c/a ratio was obtained for all the clasts and the number of clasts for which the value of c/a was less than 0.5 was expressed as a percentage of the sample size.

4.5.2 Clast roundness

At first samples of fifty clasts with diameters between -5 ϕ and -3 ϕ from each of the important lithologies at each site were compared with Power's (1953) visual comparison chart and assigned to one of the six descriptive classes. However it became evident that the writer tended to adopt certain criteria rather than make simple comparisons with the chart. Therefore these criteria were formalised and are listed below. Each of them corresponds roughly with one of Power's classes but they are considered to be more reproducible and less subjective than comparison of each clast with a pictorial representation.

Very angular: having at least one unworn edge between two faces that are acutely angled to one another (blade-like), or having a sharp, delicate protuberance.

Angular: having unworn edges but lacking the sharp features described above.

Sub-angular: having rounded edges with straight or unworn sides between them.

Sub-rounded: having faces that are worn so as to be convex.

Rounded: having edges only marginally distinguishable from rounded faces.

Very rounded: having no distinguishable edges.

Each of the six roundness classes was given a numerical value ranging from 1 (Very angular) to 6 (Very rounded). The scores for a sample were summed and divided by fifty to give a numerical expression of the average angularity of the sampled clasts.

4.6 Till-fabric analysis

The most important till-fabrics in various fluted moraines have been shown to be parallel to the ridge axes (Shaw and Freschauf 1973, Boulton 1976a, Lawson 1976). In this study some fabrics were used to test the applicability of this generalisation to moraines in Scotland and the technique was also used on features of less certain origin to compare the results with those obtained from the fluted moraines and thus elucidate the nature of the features. It was assumed that preferred clast orientations parallel to ridge-crests was indicative of ice-moulding or fluting since ridges formed by crevasse filling, squeezing of debris into subglacial cavities, or deposition from the ice surface would tend to produce weak, variable fabrics or preferred orientations transverse to the ridge crests.

Cornish (1979) has given a comprehensive discussion of this technique but for the purposes of this study it is sufficient to

describe the procedure employed. The clasts were taken from horizontal platforms near the bases of pits so as to minimise the effects of post-depositional modification although, in some cases, a second analysis was carried out near the surface for comparative purposes. The orientations of the a-axes of fifty clasts were measured to the nearest 5° using a Silva compass. Clasts were excluded from the sample for the following reasons: (i) if the a-axis was less than 1.5 times as long as the b-axis, (ii) if the a-axis was less than 1 cm long, (iii) if they were in contact with other clasts, or (iv) if they were in close proximity to a large boulder.

The results were presented on rose diagrams and, for unimodal distributions, the An_{180} statistic (Dale and Ballantyne 1980) was used to indicate the degree of clustering.

4.7 Mapping

Several different methods were used depending on the degree of detail required and the size of the area covered. The main method was to use ordnance survey 1:10,000, 1:25,000 and 1:50,000 maps as topographic bases for information derived from aerial photographs and field mapping. Geological Survey maps and the geomorphic maps of Robinson (1977) and Sissons (1977a) were used as additional source documents.

A large quantity of data was gathered in an attempt to identify different landform classes with a view to producing general geomorphic maps of the whole field area. However it proved impossible to produce a satisfactory classification since the

landforms did not fall into distinct classes. Therefore only the data for areas of particular interest are included in the thesis.

A detailed map was made of features in Coire a Cheud Cnoic. This was done by enlarging the 1:10,000 map to 1:5,000 scale. The features were added in the field, the lochans, streams and accurate photogrammetric contours providing sufficient control to locate the moraines. The map was checked by comparing it with aerial photographs.

In one area of Strath a Bhathaich where the orientation and relative positions of ridges had to be found a theodolite was employed and positions on the ridges were surveyed tacheometrically. In other areas where a limited amount of surveying was required to produce profiles and cross-sections and to determine gradients of slopes, an Abney level, tape and ranging rods were employed.

CHAPTER 5

EVIDENCE FROM THE AREA SOUTH OF AN RUADH-STAC

5.1. Introduction

5.1.1. Relief and geology

The first area considered in detail is centred on a broad rock bench, c. 2km³ in area, SE of An Ruadh-stac (Fig. 5.1). The bench is irregular but its general slope is from 550m to 360m in a south-easterly direction. The slopes of An Ruadh-stac (892m), Meal nan Ceapairean (677m) and a ridge joining these two summits constitute its northern boundary. To the S and W it is bordered by a group of small hills whose heights range from 604m to 422m. The eastern edge of the bench is defined by a steep drop into a major N-S valley (Fionn-abhainn).

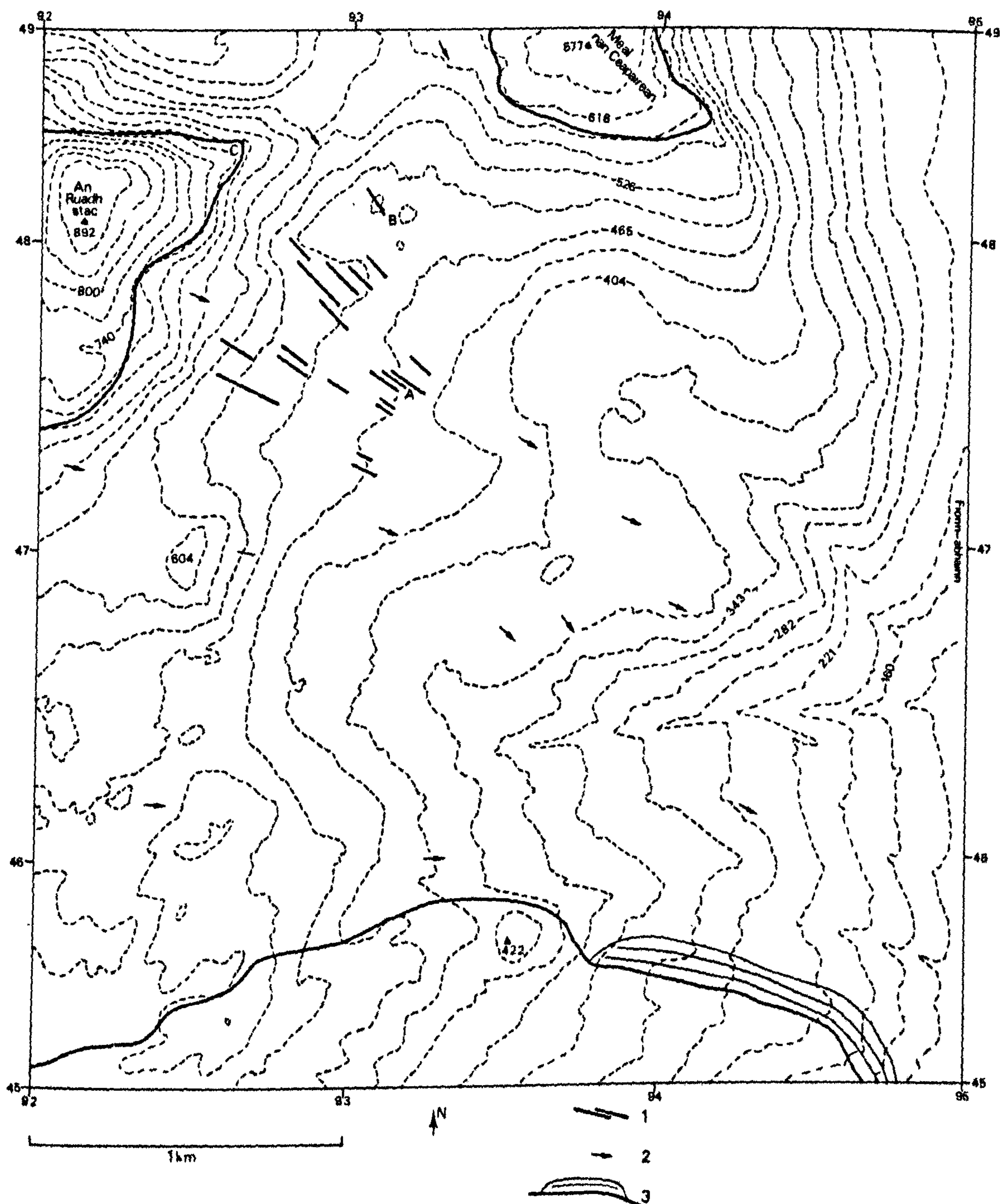
All the high ground to the NW of the bench is composed of Cambrian Quartzite, the contact between this rock and the adjacent Torridon Sandstone occurs at a fault line coinciding with the break of slope at the base of An Ruadh-stac. These strata are, again, succeeded by quartzite 400m N of Cnoc na-h-Atha (Peach et al. 1907).

5.1.2. Glacial features

A coherent, converging pattern of fluted moraines and striae crosses the bench in a SE direction (Fig. 5.1). This pattern is delimited to the S by a well developed belt of lateral moraines.

Fig. 5.1 The area studied in chapter 5

1. Fluted moraines
2. Striae
3. lateral moraines and glacier limits



These features indicate the former existence and ice-flow direction of a Loch Lomond Advance glacier. To the W there were other ice accumulations comprising an "apron" of ice that extended for over 4km. To the E the glacier was confluent with a thicker ice stream flowing southwards down Fionn-abhainn (Robinson 1977).

The best developed fluted moraines are a group of three features about 1km SE of the summit of An Ruadh-stac (Fig. 5.1, Area A). The results of detailed sampling of these features are presented later in this chapter. The extensive area of fluted moraines mapped by Robinson to the NE of Cnoc na-h-Atha (422m) is mainly composed of solid rock. The so-called moraines are the outcrops of successive beds of quartzite. The edges of the exposed strata have been rounded and smoothed by glacial action but striae on the ridges show that ice-flow was slightly oblique to them.

The only major glacial deposits on the bench are a group of large hummocky moraines situated directly below the col between An Ruadh-stac and Meall nan Ceapairean (Fig. 5.1, Area B). These features are described in detail below. Over the remainder of the area there is considerable bedrock exposure and most of the intervening hollows are occupied by peat. Numerous striae testify to glacial abrasion of the rock surfaces.

5.1.3. Glacial events of the Loch Lomond Advance

Robinson (1977) stated that:

"though there is no coire on the south-east face of An Ruadh-stac the abundant fluted moraines show that snow and neve must have accumulated on the broad, gently sloping shelf below 530m" (p. 61).

This conclusion accords with the evidence for accumulation of

ice at a similar altitude, but in the absence of neighbouring high ground, to the W of this area. Robinson also described a contrast on An Ruadh-stac between the polished and striated slabs of quartzite on the lower slopes and the frost-shattered debris higher up. Frost shattering was severe during the Loch Lomond Stadial (Sissons 1979) but the survival of the striated surfaces shows that subsequent activity has been slight. The contrast is, therefore, thought to delimit the area covered by Loch Lomond Advance ice. The writer found a sharp change in the above characteristics at c. 680m on the eastern ridge of An Ruadh-stac (Fig. 5.1, Area C). Complementary observations on Meal nan Ceapairean were hampered by the prevalence of drift on the hillside. Nevertheless frost-shattered bedrock exposures were observed down to 600m on the western slopes. These observations indicate that, at the maximum extent of the Loch Lomond Advance glaciers a considerable depth of ice existed over the ridge whose lowest altitude, at the col, is 555m. Striae on the ridge show that ice flowed across it but their trend cannot be used to determine the direction of ice movement. However, since the maximum ice surface had dropped to less than 600m a short distance SE of the col it seems likely that the flow was from NW to SE across it.

5.2. Evidence from the fluted moraines

5.2.1. Introduction

The group of features, mentioned above (Fig. 5.1, Area A), was selected for study for three reasons.

- (i) Despite their subdued form they are well defined (Fig.

5.2).

(ii) They are 400m down-ice of a change in bedrock.

(iii) They can be compared with the neighbouring hummocky moraines (Fig. 5.1, Area A).

The features occupy the surface of a low, smooth mound so their profiles are gently convex. No large boulders or bedrock knobs that could have acted as initiating obstructions (Section 3.3.2) are present.

Two of the fluted moraines are about 70m long and two pits were dug in each of these. The third ridge is 120m long and four pits were dug in it. The relative positions of these sites are shown in Fig. 5.2. (inset). The pits were all situated on the crests of the features as the swales are peat-filled. Thirteen till samples from these sites were analysed. This concentrated sampling pattern was adopted because this was the first fieldwork area and one objective was to test the techniques. Most of the till samples were taken below the iron-pan (40-50cm) to minimise the effects of post-depositional modification. In order to gain more information about the stratigraphy, especially the upper layers, the rock-type proportions of small gravel samples from 5 to 15cm depth intervals were determined. In addition some till fabric analyses were carried out, two from each of three sites.

5.2.2. Rock-type proportions

In Fig. 5.3 there is a clear distinction between samples containing 50-60% quartzite with few, if any, ice-sheet erratics, and sites having 70-80% sandstone with large components (up to 10%) of

Fig. 5.2 Cross profiles of the fluted moraines

Rock-type proportions at the sampled sites are included at the same vertical scale. The inset gives a plan view of the features and sample sites.

1. Ground surface
2. Peat
3. Sandstone
4. Quartzite
5. Ice-sheet erratics

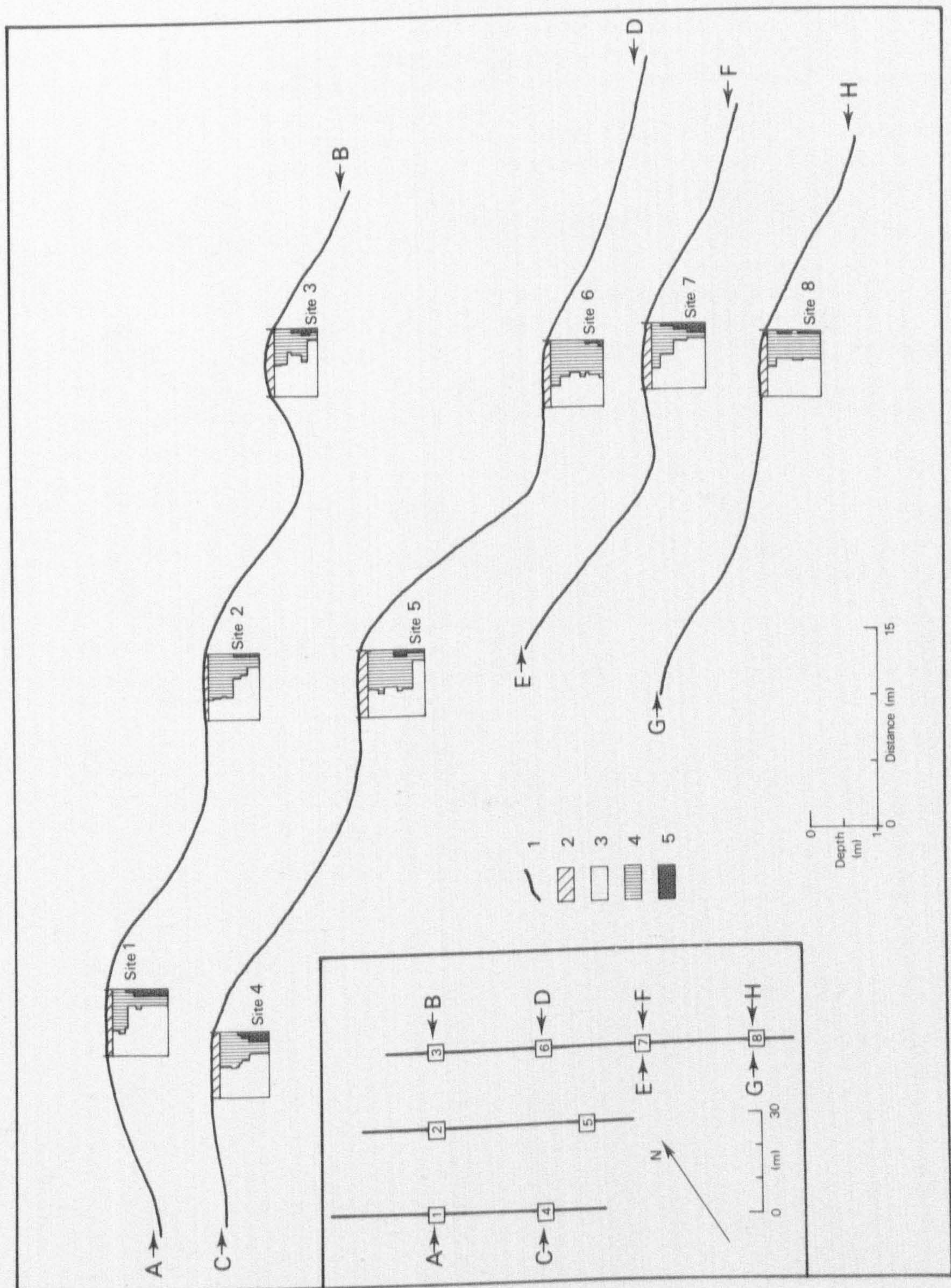


Fig. 5.3 Rock-type proportions and particle-size distributions for sites in the fluted moraines.

Each box contains samples from one site. Sites in the same feature are connected by thick vertical lines and the distances between sites are indicated. Within each box the samples are arranged in stratigraphic order and the columns to the left of the graphs indicate the depths from which they were taken.

1. Ice-sheet erratics
2. Quartzite
3. Sandstone
4. undifferentiated

Other information is given for Site 1 A and applies to all the graphs.

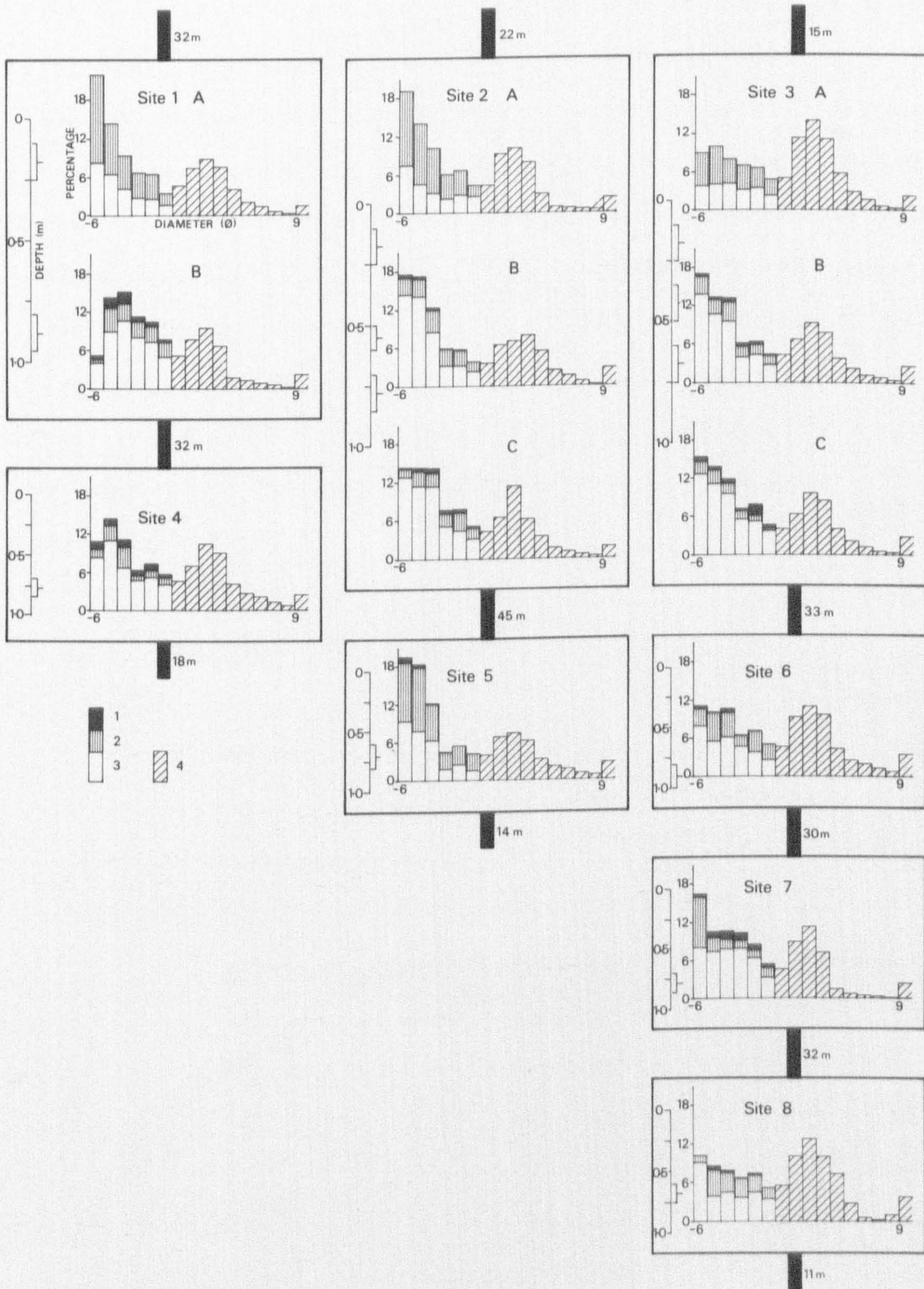


Fig. 5.4 Cumulative-percentage frequency curves
for samples from the fluted moraines

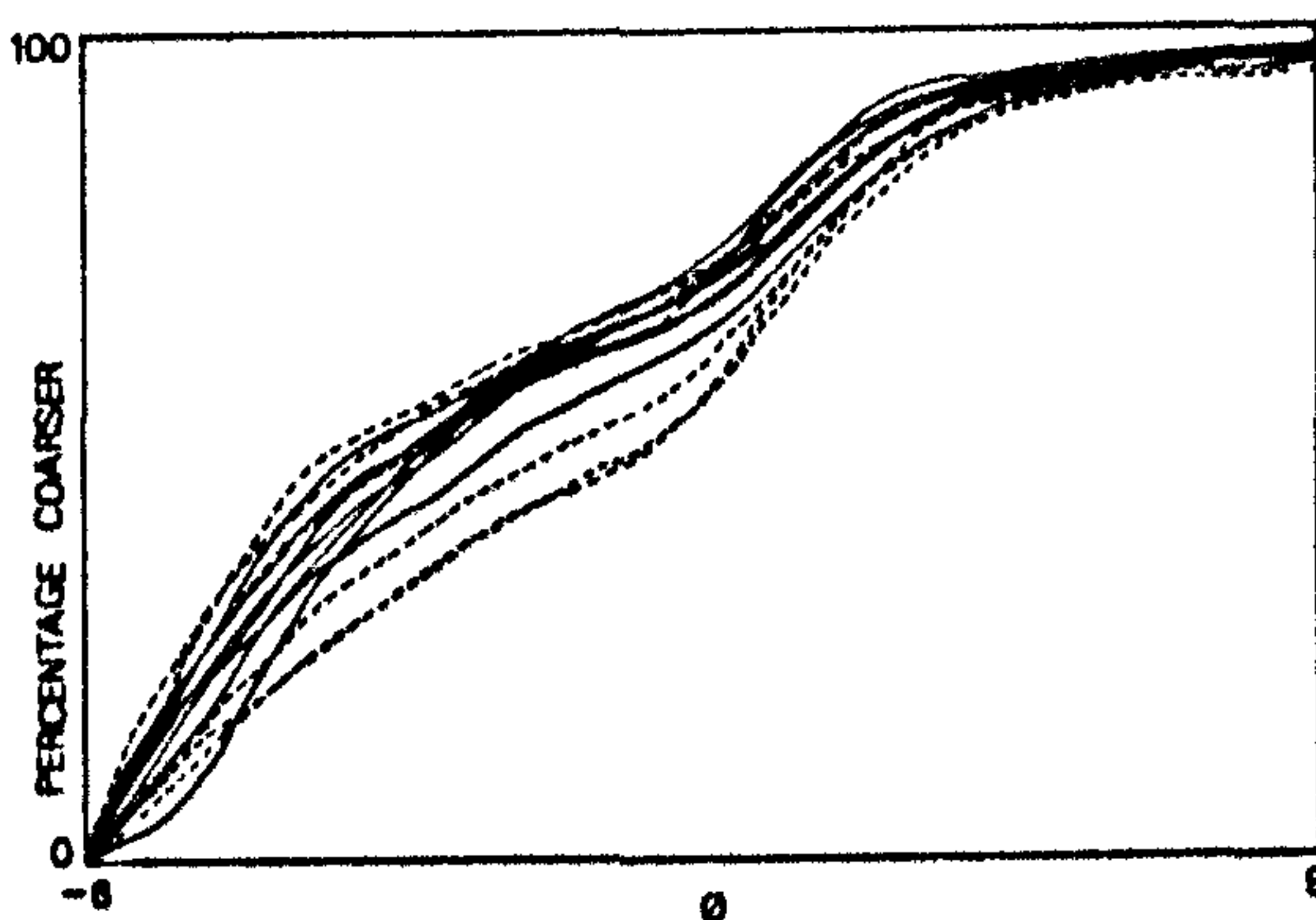
Broken lines represent samples from the
upper till.

Continuous lines represent samples from the
lower till.

ice-sheet erratics. Fig. 5.2 shows these changes in stratigraphic context with cross-profiles, on the same vertical scale, to indicate the depth of changes relative to the size of the landforms. This diagram confirms that the distinction, noted above, occurs as depth increases in six of the eight sites (1,2,3,4,5,7). In these sites the coincidence of increases in sandstone and ice-sheet erratics is pronounced. It is suggested that these characteristics indicate a stratigraphic change in the till. Therefore, in the following discussion, two groups of samples termed the upper and lower till will be compared to assess the degree and nature of differences between them. The samples assigned to the lower till are 1.A, 2.A, 3.A, 5, 6 and 8.

5.2.3. Particle-size distributions

In all the samples, as in many of those taken from other areas, the till is rich in coarse gravel and cobbles and contains some large boulders. These stones are supported by a sandy matrix to form a coherent but unconsolidated diamicton. This description is reflected



in the bimodal particle-size distributions of all the samples (Fig. 5.3). No structures or stratification were observed in the till and all sharp colour changes were attributable to soil

formation processes. Below the soil horizons the till was usually light pink or yellow in colour.

In cases where two samples have been taken from the same type of till in the same pit the particle-size distributions are almost identical (Fig. 5.3, samples 2.B, 2.C, 3.B and 3.C). There is also great similarity between the samples from these two adjacent sites. In Fig. 5.4 the cumulative percentage frequency curves of lower till samples are marked by continuous lines and all these curves pass through a narrow envelope. Therefore, either the lower till has a consistent particle-size distribution and the sampling procedure gives an adequate representation of it, or the till is variable and errors in the sampling technique are redressing the differences caused by this variability. The first of these possibilities is the most likely.

Samples from the upper till (dashed lines in Fig. 5.4) are similar to those from the lower till but they are more variable, three of them being relatively poor in gravel. This minor difference may be the result of granular disintegration which may have occurred owing to frost action since deposition. However, this effect should be limited to debris exposed at the ground surface. Alternatively, some supraglacial debris may be included in the upper samples. This possibility is dealt with in Section 5.2.6.

The main conclusions are that the sampling procedure is adequate and that there are no major or consistent differences between the particle-size distributions of samples from the lower and upper tills.

Fig. 5.5 Till fabric analyses from the fluted moraines

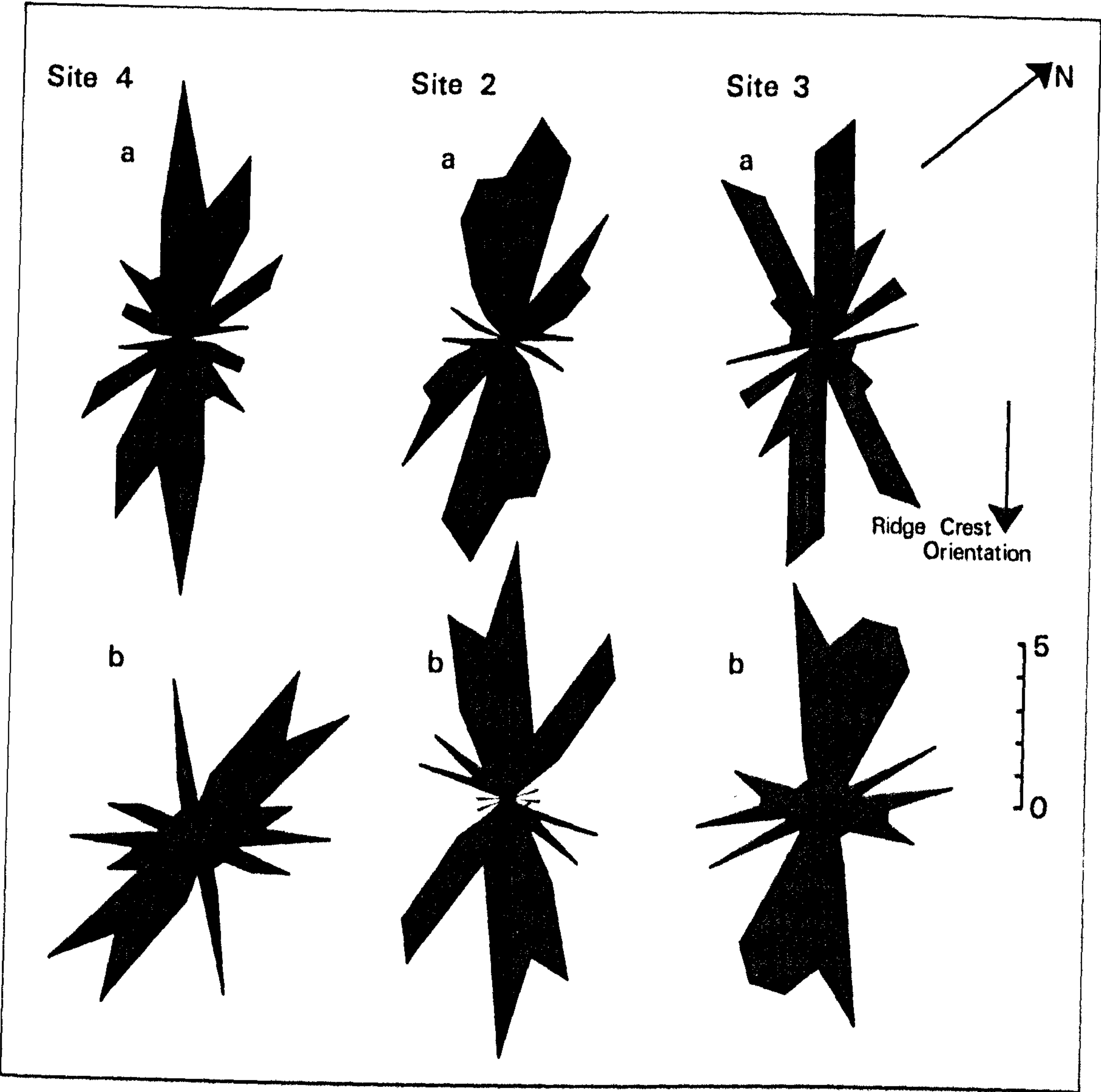
Two fabrics were measured from different depths at each of three sites and the probability of the clustering occurring by chance was measured with the A_n 180 statistic.

Site	Sample	Depth (cm)	A_n 180	Propability
4	A	30-40	1.3163	>0.001
	B	>80	0.6674	>0.1
3	A	10-20	1.8106	>0.001
	B	65-75	1.9849	>0.001
4	A	10-20	1.1652	>0.005
	B	50-60	0.7269	>0.05

Fig. 5.4 Cumulative-percentage frequency curves for samples from the fluted moraines

Broken lines represent samples from the upper till.

Continuous lines represent samples from the lower till.



5.2.4. Clast form and roundness

These variables have not been measured at all the sites. This is because, during sampling, it was not considered necessary to measure the characteristics of a rock type that only constituted a small proportion of the till.

The Mann-Whitney U test has been employed to assess whether significant differences occur between groups of samples.

Comparisons between sandstone and quartzite samples

The form of stones in the samples is variable, the percentage of elongates (c/a axial ratio < 0.5) ranging from 12% to 68%. The sandstone samples usually have larger proportions of elongates than the quartzite samples (n=28, U=55). Thus the quartzite and sandstone samples differ from one another at the 0.05 level of significance).

The roundness of clasts from different sites does not vary greatly and the means of all the samples fall in the sub-angular class. There is no significant difference between the quartzite and the sandstone samples.

Comparisons between the upper and lower tills

The Mann-Whitney U test showed that there was no significant difference between average clast roundness and form for samples from the upper and lower till at significance levels of 0.05 and higher.

5.2.5. Till fabric analyses

Five of the six analyses (Fig. 5.5) show preferred orientations of clasts parallel to the ridge crests (4.a, 2.a and b, 3.a and b). The lower sample from Site 3 has another peak perpendicular to that

direction. Such a secondary transverse mode has often been identified in till fabrics (e.g. Glen et al. 1957). A different secondary orientation, aligned approximately N-S occurs in Site 2 (a and b) and site 4 (a and b). In all these cases the fabrics are statistically significant despite the secondary mode. In the lower fabric taken from Site 4 the N-S fabric is the dominant mode and here the fabric is only significant at the $p = 0.1$ level. The fact that this orientation is most strongly developed in the fabric measured at the greatest depth and that it occurs as a secondary mode in three other fabrics demands explanation (Section 5.2.6).

Two of the fabrics (Site 2.a and site 3.a) were measured at depths of less than 20cm. Strong orientations parallel to the ridges are displayed in both cases. Any post-depositional modification of the surface layers would have tended to randomise the pattern (e.g. plant activity or frost sorting) or to produce a downslope (transverse) orientation (e.g. solifluction). Thus the existence of strong, ridge-parallel orientations, which are significant at the 99.9% and 99.5% confidence levels respectively, show that these agencies have not been important. Similarly, if the till was deposited from a supraglacial position it would be unlikely to adopt the observed orientation. Therefore these measurements indicate that the surface layers of the till were deposited as part of the fluted moraines.

In general the results conform to the expected pattern for fluted moraines (Boulton 1976a) and do not display clear differences between the upper and lower tills. The unexplained N-S trends are discussed in Section 5.2.6.

5.2.6. Discussion of the results

The simplest explanation of the upper, quartzite-rich till is that it may be composed, wholly or partly, of debris carried at a high level in the ice and superimposed on the fluted moraines. This explanation is rejected for the following reasons.

(i) The features are subdued (Fig. 5.2) yet they are clearly defined. If they had been buried by debris, in any form other than a uniform blanket, they would have been masked by it.

(ii) Differences between the upper and lower tills have been sought. There is a contrast in rock-type proportions but the other variables show only small differences if they differ at all. If the two tills had supraglacial and subglacial origins a contrast in particle-size distribution, clast form and clast roundness would be likely (Mills 1977a, 1977b; Boulton 1978).

(iii) The occurrence of strong preferred orientations of clasts, parallel to the ridges, in the upper till, shows that this till is part of the features.

Assuming that the upper till was deposited by Loch Lomond Advance ice flowing SE from An Ruadh-stac two explanations of the evidence can be given.

In the first explanation one could assume that the lower till was deposited by the Late-Devensian ice-sheet. If it dated from this time it was probably deformable during the Loch Lomond Advance. This is suggested because, if it was rigidly emplaced (frozen for instance) it would be unlikely to display clast orientations exactly parallel to the ice flow of this latter event. In addition the

contrast between it and the locally eroded Loch Lomond Advance till would be more pronounced and the junction between them would be sharper. This explanation implies that the fluted moraines are superficial features and that they could have been formed in a short period.

In the alternative explanation the lower till is attributed to an early stage of the Loch Lomond Advance. At this time many ice-sheet erratics would have been available to the glacier. As time passed some erratics would have been transported down-valley, others would have been deposited in more stable positions and the remainder would have proved themselves less amenable to redistribution. Sandstone would have been derived from older deposits and from erosion of bedrock. The first of these sources would have declined in importance in the same way as the supply of ice-sheet erratics. By contrast most of the quartzite would have been eroded from An Ruadh-stac and this source would not have been affected by a depletion of supplies. Therefore the importance of quartzite in the till would have increased as the abundance of sandstone and ice-sheet erratics diminished. If this process occurred a steady stratigraphic gradation of rock types might be expected in the till. The sharpness of the change observed in the fluted moraines could be explained as being the result of a non-uniform rate of deposition or a phase of erosion between two periods of deposition.

The real difference between the two explanations is probably only the degree to which the pre-existing debris was reworked by the Loch Lomond Advance glacier.

The idea that the lower till may be ice-sheet material that has

been modified only slightly by the Loch Lomond Advance glacier offers the following resolution of the problematic N-S orientations observed in four fabric analyses. During the wastage of the Late-Devensian ice-sheet relief would have exerted increasing control on ice-flow direction. The direction of steepest ground slope here is to the SE but ice-flow in this direction would have constituted a complete reversal of the earlier regional pattern. A southward movement of ice, towards Strathcarron would have been more likely to occur and could have produced the observed N-S orientations.

5.2.7. Conclusions

(i) The sampling procedure provides an adequate description of the till.

(ii) The features were formed as a result of subglacial deposition in ridges parallel to ice-flow.

(iii) Supraglacial and englacial contributions were small.

(iv) Some of the unconsolidated debris that was present before the Loch Lomond Advance, including ice-sheet erratics was transported less than 500m during that event.

(v) Ice-sheet debris has undergone some reorganisation during the Loch Lomond Advance.

5.3. Evidence from the hummocky moraines

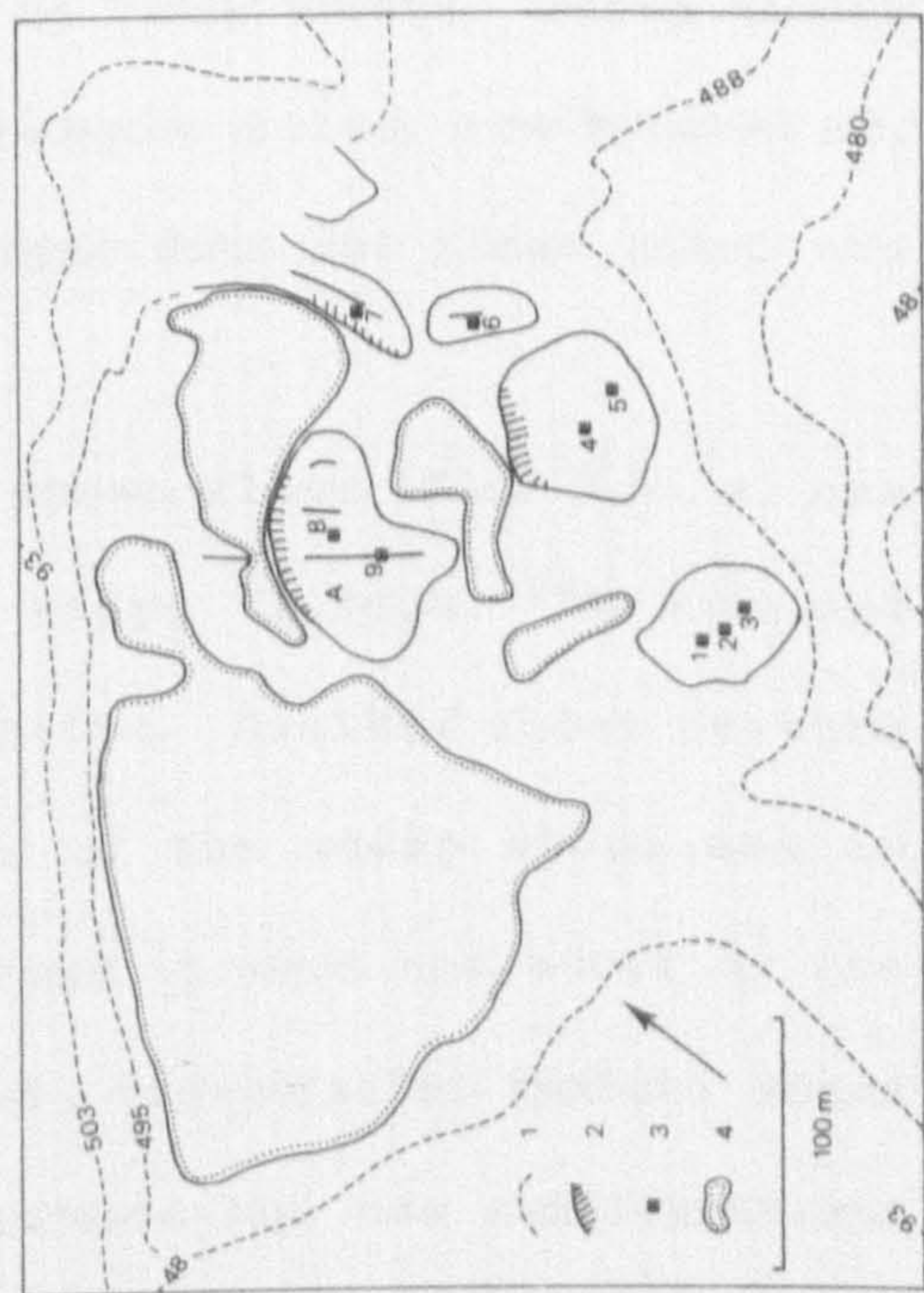
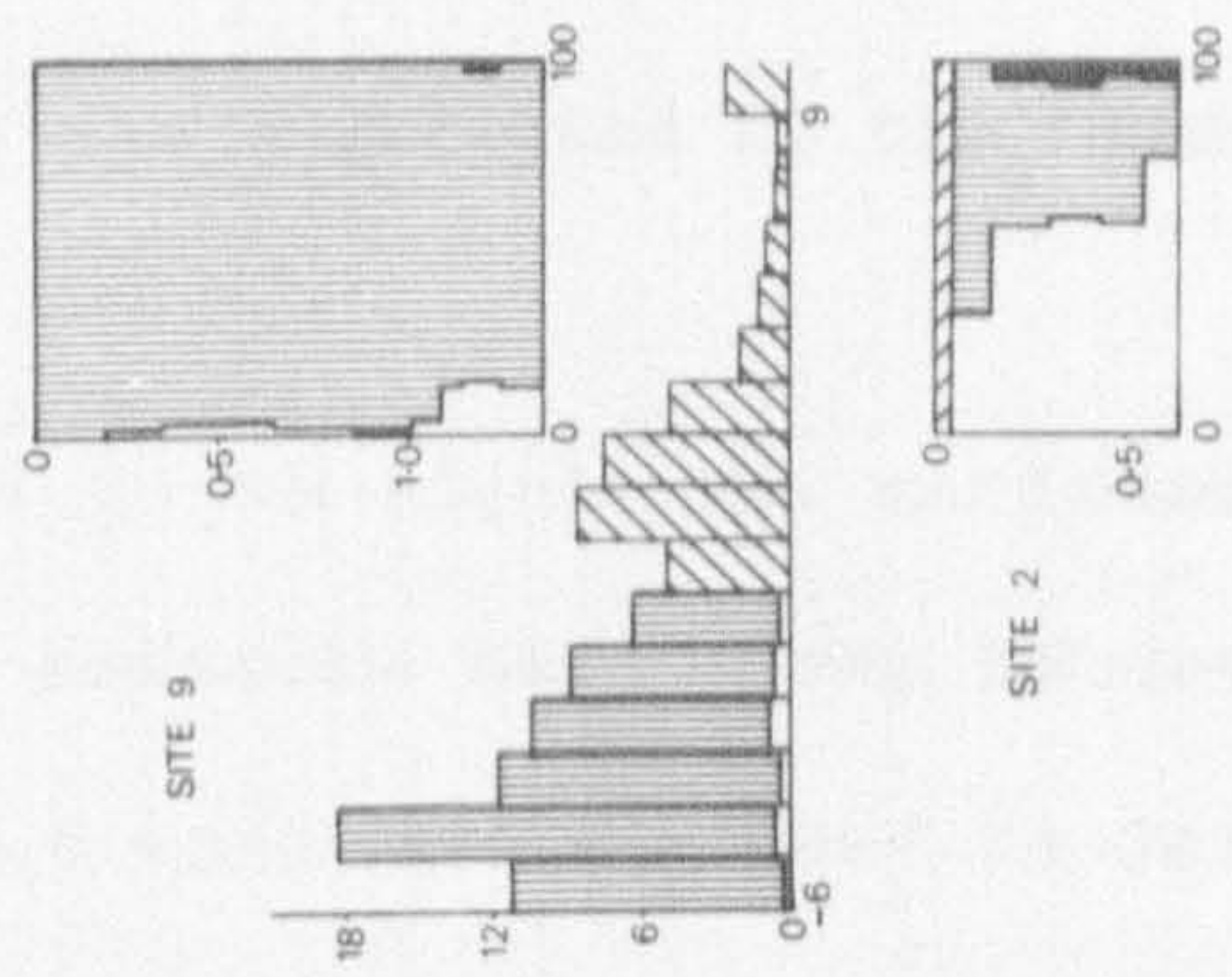
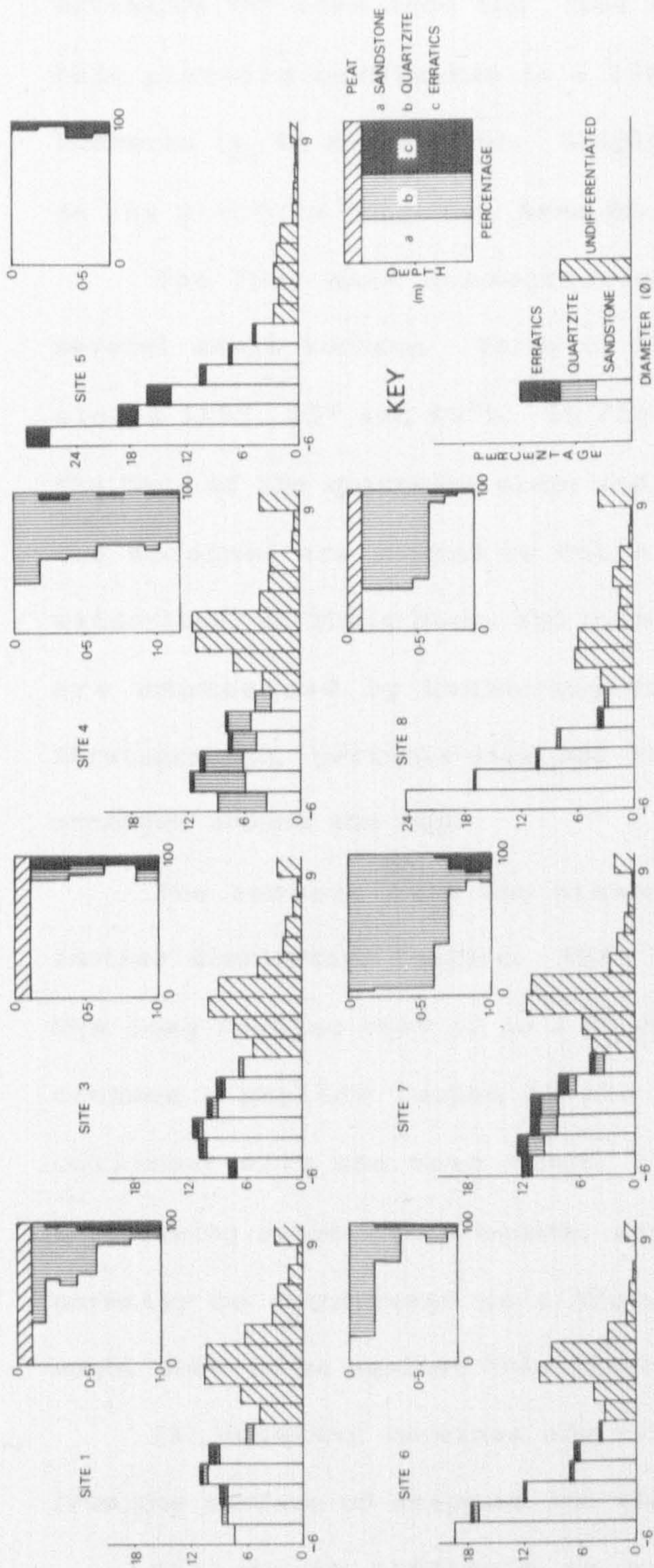
5.3.1. Introduction

These features, situated below the col, have been mentioned above. The four largest features occupy a sandstone platform,

Fig.5.6 Data from the hummocky moraines

1. Contours
2. Steep mountain slopes
3. Sample sites
4. Lochans

Particle-size and rock-type proportions are given for the samples from each of seven sites. An additional diagram shows the variation in rock-type composition with depth at all the sites. See Key on diagram.



extending for 250m from the foot of the quartzite slope. To the SE this platform terminates in a 20m rock step below which smaller hummocks (c. 5m high) occur. Sampling was restricted to the features on the platform (Fig. 5.1, Area B).

The four main hummocks rise 6 to 8m above the surfaces of several small lochans. Three of the hummocks have steep NW-facing slopes (25° , 35° and 40°). In Fig. 5.6 contours are used to define the base of the quartzite slope and the position of the rock step but the moraines are mapped by delimiting the break of slope, or the water-line, at their bases and by marking ridge crests. Steep slopes are emphasised by hachuring and sample sites are numbered. Stratigraphic, particle-size and rock-type data for these sites are arranged around the map.

The hummock with the steepest stoss slope (Fig. 5.6, A) has another distinctive feature. This is a ridge, 1m high, 15m wide and 60m long running over it in a SE direction. Another short feature crosses a shallow lochan at the base of the steep slope and is collinear with the main ridge, although it does not occur on the intervening slope. This smooth, straight, ice-parallel feature would normally be interpreted as a fluted moraine but two considerations might seem to be against this interpretation.

(i) Hummocky moraines are normally considered to be deposited from the surface of stagnant ice (Section 3.4.1).

(ii) It is difficult to envisage a fluted moraine being deposited over an undulating landscape including a 4m high, 40° reverse slope.

The hummocky moraines were studied for three reasons.

(i) They occur in an ice-source area on sandstone but immediately down-ice of a steep quartzite slope.

(ii) It was hoped that the problem described above could be resolved.

(iii) Most of the area is littered with angular quartzite clasts, but small patches of sandstone-rich debris are exposed on the summits of two of the features (around Sites 3 and 5). Thus it was necessary to determine whether the sandstone debris was a superficial capping or whether it was an exposure of the core of the features which had, elsewhere, been mantled by quartzite.

5.3.2. Rock-type proportions

Sampling of the small-gravel fraction at short stratigraphic intervals showed that, in five cases, the sandstone and ice-sheet erratics percentages increased with increasing depth in the till (Fig. 5.6, Sites 1,2,6,7,8). In Sites 3 and 5 there is no surficial quartzite and here the pattern did not change with depth. Site 4 did not display a big reduction in quartzite and at Site 9 very little sandstone was found in the till despite digging down to 1.35m. This site is situated in the ridge described above. The eight main till samples confirm that the small gravel samples are representative of the other size fractions.

5.3.3. Particle-size distributions

The eight samples can be considered as two groups, "coarse" and "fine", on the basis of their particle-size distributions. The

samples in the "fine" group (1,3,4,7) have a mode in the sand fraction, which is almost as important as the mode in the gravel fraction. These samples have a smaller mean diameter than most of the samples taken from the fluted moraines.

The samples in the "coarse" group have small secondary modes in the sand fraction and at Site 5 this peak is almost absent. Indeed only 10% of this sample is composed of particles finer than 1 ϕ (0.5 mm) and it is the second coarsest till sampled during the whole project.

Another feature of this division into two groups is that, with the exception of Site 9, the coarse samples have far smaller percentages of ice-sheet erratics than the finer samples. The former group has values between 0% and 1.4% and the latter group ranges from 4.5% to 8.7%.

5.3.4. Clast roundness

The proportion of quartzite in many of the samples is insignificant so, in these cases, measurements of clast roundness and form were confined to the sandstone. At Site 9 the sandstone is an insignificant component and measurement was, therefore, confined to the quartzite.

The mean values of roundness of sandstone clasts from the samples are variable. Two of them fall in the angular class and one falls in the sub-rounded class. The "coarse" group has significantly more angular sandstone clasts than the "fine" group ($n=7$, $U=1$, indicating that the samples are different at the 0.057% level of

significance). The most angular sample was taken from Site 5. The exceptional nature of this sample can be emphasised by stating that on average it contained the most angular sandstone clasts recorded in the whole project.

5.3.5. Clast shape and slickensides

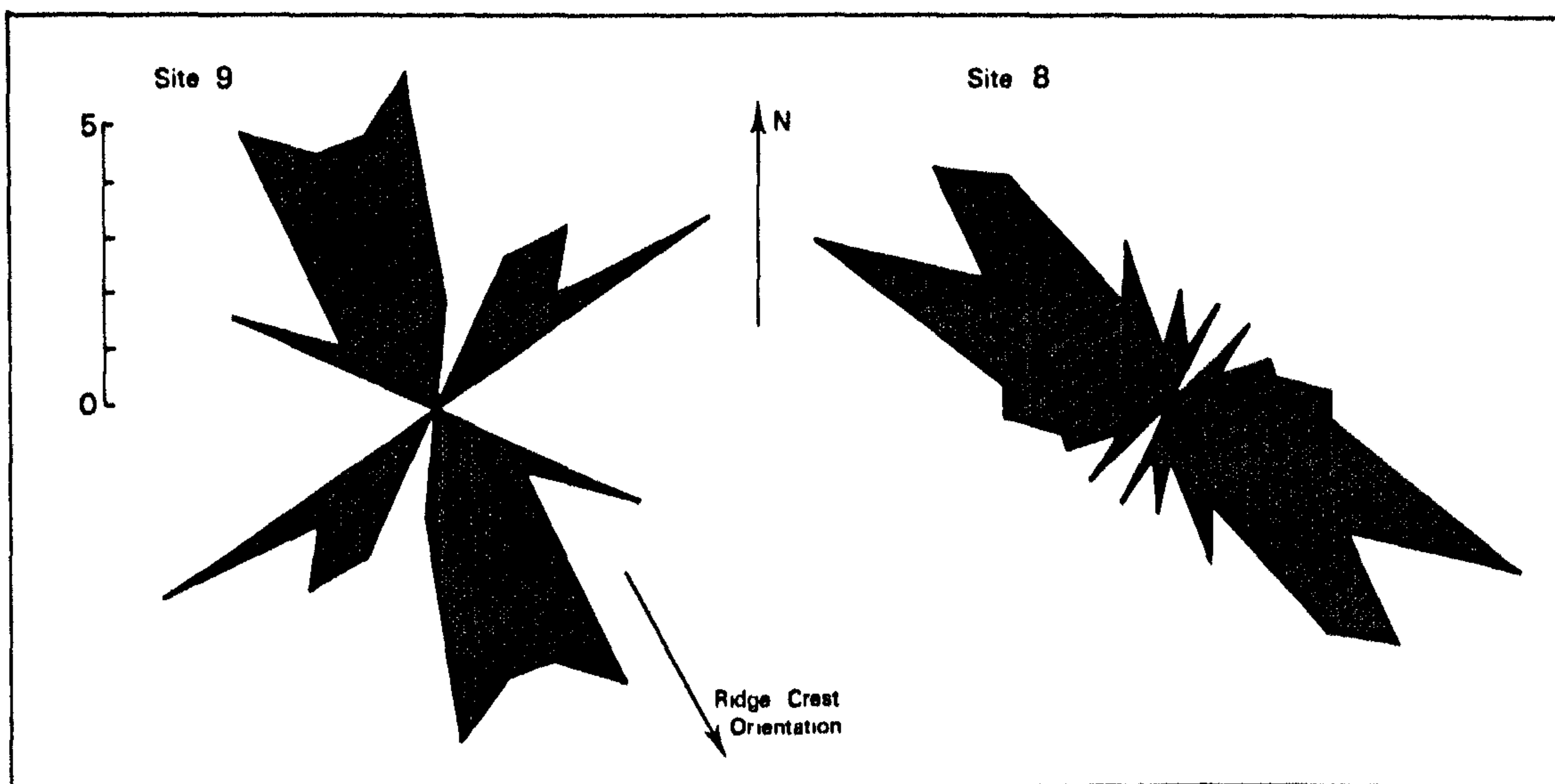
Measurements of the form of sandstone clasts show a wide variety of proportions of elongates in different samples, the range being from 20% to 52%. There is no significant difference between the 'coarse' and 'fine' groups of samples. Sample 5 contained the highest proportion of elongates. Another feature of the clasts in sample 5 is that the majority of them have one or more green vitreous surfaces on many of which delicate slickensides are visible. These surfaces are planes along which minor fault movement has occurred. During erosion of the rock these planes have been exploited. Similar clasts occur at Sites 4, 7 and 8 but they are a less important component of the till in these samples.

5.3.6. Till fabric analysis

Only two till fabric analyses were undertaken (Fig. 5.7). One of these was at Site 9 and revealed a preferred orientation parallel to the ridge crest. This increased the confidence with which this feature could be termed a fluted moraine. Another fabric, measured at Site 8, revealed a strong preferred orientation at a slightly different angle. This also suggests the influence of ice movement away from the quartzite ridge.

Fig. 5.7 Till fabric analyses from Sites 8 and 9

Site	Depth (cm)	A _n 180	Probability
8	80-90	1.3729	>0.001
9	90-100	1.4856	>0.001



5.3.7. Discussion of the results

Sampling of the till shows that despite the position of these features, immediately down-ice of quartzite bedrock, they are mainly composed of sandstone. The following discussion deals with the problem of how the sandstone-rich material accumulated in this area. Initially it can be stated that it could not have a supraglacial source because the only high ground in the vicinity is composed of quartzite.

Some of the sandstone may be the result of very local erosion and deposition by the Loch Lomond Advance glacier flowing across the area from or over the quartzite headwall. The remainder can only have been deposited by the Late Devensian ice-sheet.

Debris from each of these sources would be expected to have different characteristics. The processes of attrition that occur during transportation at the base of a glacier would have quickly destroyed delicate features such as slickensides. They would also

have led to a rounding and comminution of the stones. In addition elongate stones would have been more susceptible to fracture than compact ones. Fractures would have tended to be in a plane perpendicular to the principal axis and, in these cases, would have resulted in two, more compact, stones. Thus the occurrence of a high proportion of elongate stones, slickensides on stone surfaces, angular edges and coarse particle-size distributions are all indicative of a short distance of transport. Conversely a high proportion of ice-sheet erratics indicates that much of the till is not local.

It has been pointed out that the coarse samples are more angular and have lower percentages of erratics than the finer samples. This indicates that the former group of samples contains a larger proportion of locally derived material. The sample from site 5 has the highest proportion of elongates, the most angular clasts, the coarsest particle-size distribution and the most clasts with slickensides. All these facts indicate local origin, but it also has the highest proportion of ice-sheet erratics. It is suggested that this exceptional sample is best explained as consisting of end-moraine material accumulated at an early stage of the Loch Lomond Advance, when ice-sheet erratics were abundant, and subsequently overridden by the ice. This explanation can account for the prevalence of very locally quarried clasts mixed with a large content of ice-sheet erratics.

The survival of a large proportion of ice-sheet debris and of supposed end-moraine deposits shows that much of the debris was present before, or at, the start of the advance. The fluted moraine shows that at least one of the hummocks had its present morphology

before a period of active ice flow. It is simplest to consider that there was only one period of active ice flow and that all the features were formed during or before it.

This explanation poses several problems.

(i) How did these large, steep-sided hummocks survive, some of them perched on the edge of a rock step, under active ice?

(ii) How was the fluted moraine deposited over this undulating terrain (including a 6m high, 40°, reverse slope)?

(iii) Why is the debris in the fluted moraine so different from that in the underlying hummock (Fig. 5.6, Sites 8 and 9)?

The simplest way of resolving the above three problems is to say that the hummocks were frozen in place before the advance or became frozen under the ice. The first of these does not explain the till that appears to have been eroded locally by the Loch Lomond advance glacier. The second is difficult to envisage under an accumulating ice-mass because as ice depth increases pressure increases and so the temperature required to cause freezing is depressed.

The preferred explanation is as follows. Ice began to accumulate on and amongst large volumes of loose ice-sheet debris and easily erodable bedrock material. As the ice began to move this material it became, either heavily charged with englacial till and therefore less mobile, or retarded behind large mounds of debris that it had created. Subsequently cleaner, more mobile ice passed over this mixture, exerting little stress on the debris. If large differential movement occurred at a particular level in the ice a plane analogous to a glacier base would have been created. The

quartzite-rich fluted moraine could have been "deposited" in this position and, later, superimposed on the undulating, sandstone-rich hummock by basal meltout. A specific characteristic of this location that can be invoked to provide a distinct plane of differential movement in the ice is that the local ice was superseded by ice from north of the col at some stage of the glacial event.

5.3.8. Conclusions

(i) The debris in the hummocky moraines is not supraglacially derived.

(ii) Some debris that was present before the Loch Lomond Advance or produced at the onset of that event was moved less than 200m during it.

(iii) The features were not formed during ice wastage and active ice flow occurred after their formation.

5.4. General conclusions

The occupation of this area by a Loch Lomond Advance glacier resulted in limited geomorphic effects. Striae on the large areas of exposed bedrock show that the glacier achieved some erosion by abrasion, and work on the depositional features has provided some evidence of erosion by quarrying, such as quartzite-rich till in the fluted moraines and angular sandstone clasts in the hummocky moraines. The glacial deposits are concentrated in the source area and have comparatively little volume. This allowed a dense sampling pattern to be adopted which served to test the techniques (by mutual

comparison) and provided some detailed conclusions. It is clear that some debris has been moved very little by the Loch Lomond Advance glacier and that supraglacial deposition has been unimportant throughout the area. It has been suggested that at least one hummocky moraine assumed its present morphology at an early stage of the event.

CHAPTER 6

EVIDENCE FROM STRATH A BHATHAICH

6.1 Introduction

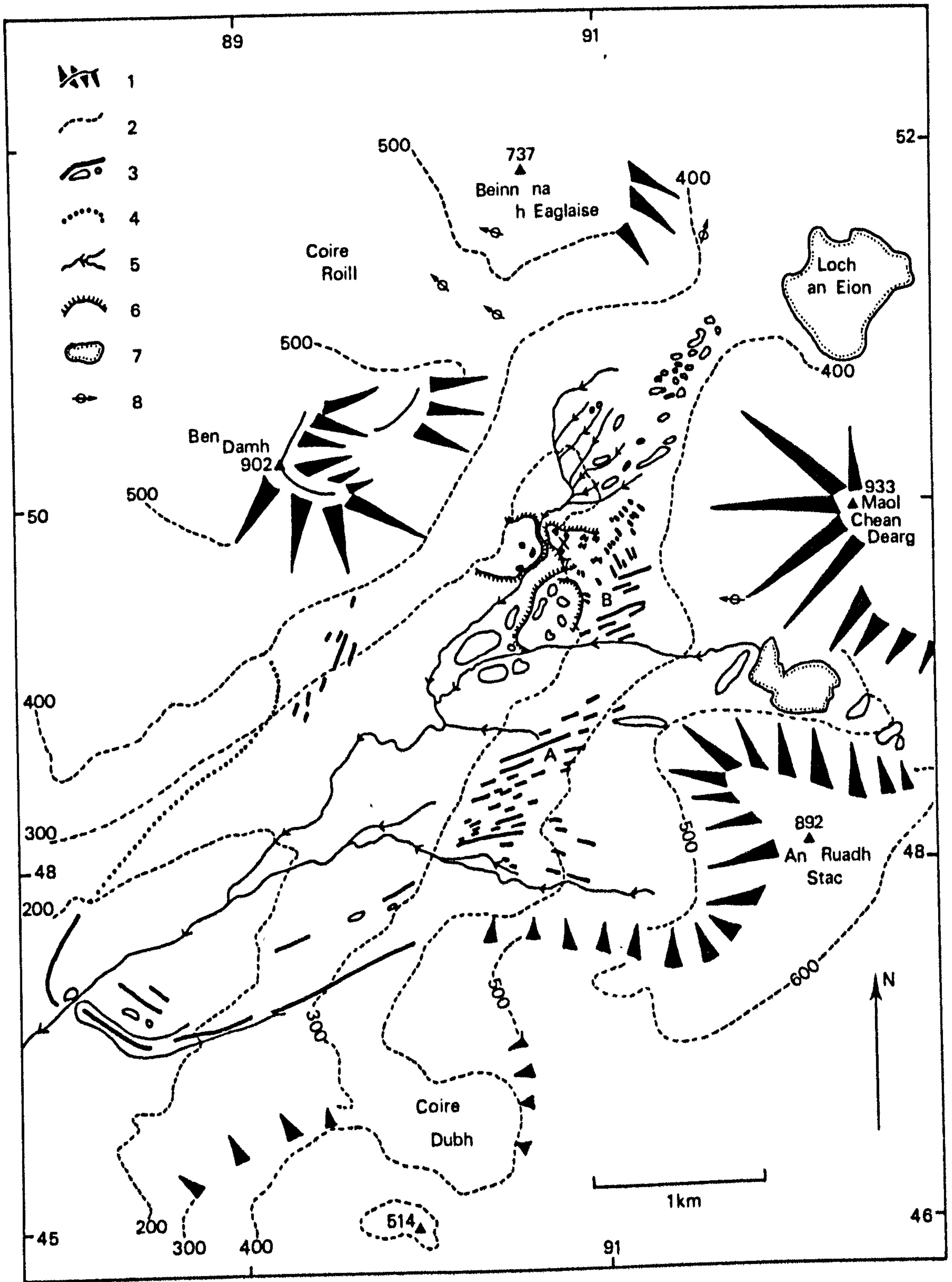
6.1.1 Relief and geology

The second area of detailed study is centred on a SW-draining valley, Strath a Bhathaich (Fig. 6.1). The SE side of the valley is composed of a series of hills culminating, to the NE, in Maol Chean-Dearg (933m). From these hills spurs project towards the valley floor and three corries occur between the spurs. The NW side of the valley is guarded by Beinn Damh (902m) and Ben na-h-Eaglaise (737m), the former having a small corrie on its SE side. The valley sides are breached by three cols: to the NE a broad col (below 400m) leads to Loch an Eion; to the NW a narrower pass, at an altitude of less than 500m, leads to Coire Roill; and to the SE the head of Coire an Ruadh-stac is at 555m (Chapter 5)

The valley is at the W edge of a zone of thrusting in advance of the Moine Thrust. Two thrust planes trend SW-NE along the SE side of the valley. these thrusts have brought forward "heaped up" quartzite which crops out in sub-parallel belts on the slopes of Maol Chean-Dearg and An Ruadh-stac, and in the floors of Coire an Ruadh-stac and Coire nan Cadham. To the NW of this area the floor of Strath a Bhathaich is composed of sandstone strata in a great anticlinal fold whose axis follows the valley. The summit of Beinn Damh is capped by quartzite lying over the sandstone in its original, unconformable manner. The Geological Survey Memoir for the area

Fig. 6.1 Strath a Bhathaich

1. Mountain ridges and steep slopes
2. Contours (100 m interval)
3. Moraine ridges and mounds
4. Drift limit
5. Streams
6. Moraine bluffs
7. Lochans
8. Striae



(Peach et al. 1907) includes a section through Maol Chean-Dearg and Beinn Damh (Fig.53,p. 506).

9.1.2 Glacial features of the area

The corries and breached watersheds mentioned in the previous section constitute impressive evidence of glacial erosion of this valley and its vicinity. This section concentrates on the depositional features that cover the valley floor. Robinson (1977) devoted over six pages (pp. 46 to 52) to description and discussion of the features. They exhibit the greatest variety of forms and probably contain the greatest volume of till of any assemblage of features studied in the project.

During the Loch Lomond Advance the valley was occupied by a glacier which left copious deposits. Its maximal extent is marked by a large end moraine up to 20m high and 500m long; both ends of this feature are continued obliquely up the valley sides by lateral moraines. The lateral moraine on the NW side of the valley runs for 500m before being succeeded by a clear drift limit that can be followed for another 1.5km. The feature on the SE side of the valley runs for 1.5km across the mouth of Coire Dubh, indicating that this corrie did not contribute ice to the main glacier. Three smaller end moraines occur, within a distance of several hundred metres, inside the main feature and parallel with it. An inner lateral moraine belt runs up the SE valley side parallel to the outer feature.

Due to the abundance of glacial drift, striae are of limited use as indicators of former directions of ice-flow. This role is

partly filled by fluted moraines which are well developed in two areas (Fig. 6.1, A and B) and also occur on the NW side of the valley, S of Beinn Damh.

N of Area B there are two sets of ridges aligned in the directions indicated on the map. The ridges of the north-easternmost group, aligned directly down the steep valley side, are often slightly sinuous and do not have smooth crestlines. They are formed almost exclusively of angular quartzite pebbles from 0.5 to 2cm in diameter. In view of these characteristics it seems likely that the debris is the product of frost-shattering of quartzite farther up the hillside and subsequent downslope movement. The morphology of the features is problematic but the presence of ice may be invoked to explain the esker-like character of the ridges. A short distance to the SW the ridges stand on a shallower gradient. They are aligned in a more northerly direction than the other group and are therefore oblique to the valley-side slope. They also differ in being straight and having smooth crests. These features, which are up to 2m high, would normally be considered as fluted moraines but they are adjacent to and run almost perpendicular to the fluted moraines of Area B described above (Plate 6.1). In one place a subdued ridge runs into a far larger fluted moraine (3m high) and is truncated by it. Robinson (1977) considered that in this area the fluted moraines of Area B had been superimposed on the adjacent ridges. The interface between these sets of features is described in detail in Section 6.3.

Robinson also noted superimposition of ridges trending in different directions around X (Fig. 6.1); here the alignments are SE-NW and down-valley (i.e. SW-NE). In this area the ridges rest on a great mass of till delimited by steep bluffs up to 12m high (Fig

Plate 6.1 Ridges at the north end of Area B

Some of the fluted moraines of area B run across the foreground of the picture and the ridges trend away from the camera in the background. Sample pits 7,8,10 and 11 are visible (cf. Fig. 6.3)

Plate 6.2 The Floor of Strath a Bhathaich and the slopes of An Ruadh-stac

The fluted moraines of Area B run across the centre of the photograph and the large bluffs of Area X occur in the valley floor.



82A

6.1, Plate 6.2). The prominence of these features may be due in part, to trimming by the river that flows through them, but where small hummocks occur below the bluffs this possibility is precluded. In Area X the ridges are associated with hummocks that do not have elongate crest-lines and with two deep kettleholes; thus the amplitude of the assemblage is far greater than at Area B, being about 6m. Plate 6.2 illustrates this area: the bluffs are particularly prominent and it can be seen that some ridges run down the front of the upper bluff in the right-hand part of the photograph. These ridges are contiguous with and similar to the features N of Area B although they run in a rather different direction. Since no bedrock crops out in Area X, even in the stream bed, the height of the bluffs only gives an indication of the minimum depth of the till.

To the SW subdued mounds on the surface of evidently deep till, without bedrock exposures even in the stream bed, occur along the valley floor for about 1km. Farther down-valley the till is still deep but has little surface expression. In contrast the area to the NE of X has small (<6m high), steep-sided hummocks and numerous exposures of bedrock indicating that the volume of till is relatively small. This area seems to display a down-valley lineation when viewed on aerial photographs but few of the individual features are elongate in this direction. Close inspection of the area reveals a pattern of dry channels running approximately parallel to one another through the features. The channels may be responsible for the apparent lineations.

In Coire an Ruadh-stac there are three large features. One of

these is a narrow ridge 4 to 6m high, extending for 300m across the mouth of the corrie. The other two features occur above the lochan and, although they are wider (across the corrie) than they are long, they cannot be described as ridges. These features are discussed in Section 6.1.3.

It was because of the close association of a diverse range of depositional features and the presence of a large volume of debris that the valley was selected for study. It was hoped that the features and the relations between them would cast light on the time and mode of deposition of the debris.

6.1.3 Glacial events of the Loch Lomond Advance

Initial ice-accumulation probably occurred in the corries (Coire an Ruadh-stac, Coire Cadham and that on Beinn Damh). Ice may also have accumulated on the high ground around Loch an Eion but, from here, it would not have been channelled towards Strath a Bhathaich as two other valleys drain N and SE from the area.

Since, at first, ice-flow would have been directly down slope the glaciers from Coire An Ruadh-stac and Beinn Damh would have flowed towards one another. Clearly, directly opposing flow could not have been maintained and several different patterns of flow may have occurred before the glaciers from these and other source areas achieved an integrated pattern in which each ice-flow was constrained by slope and other ice-masses to form a unified stream flowing towards the glacier snout.

Most of the fluted moraines are aligned obliquely to the slopes on which they stand. This situation is compatible with the situation

described above which would have prevailed at or around the time of the glacier's maximal spread. The survival of these features implies either that deglaciation was by slow-moving, down-wasting ice or that the features survived later stages of flow which would have been less influenced by ice from different sources and, therefore, increasingly related to the slope.

Another consideration is that as the ice surface rose, during glacier advance, it would have become an accumulation area over the upper valley and the relative importance of ice-flow from the corries would have been reduced. Striae on the SW flank of Ben na-h-Eaglaise and fluted moraines in Coire Roill leading away from the col show that ice flowed NW out of the valley. Ice difffluence also occurred at the head of Coire An Ruadh-stac (cf. Section 8.1.3). The position of the ice-shed to the NE cannot be accurately defined but a set of striae on the SE side of Ben na-h-Eaglaise indicates that ice at this point flowed to the NE.

Ice limits on the mountain sides are not known because the slopes are either steep rock faces or covered by drift. Robinson's reconstruction of the ice-surface at the maximum extent of the glacier (based on extrapolation of the gradients of the lateral moraines) puts it at 600-700m over much of the upper valley.

The inner end and lateral moraines show that ice retreated actively for the first few hundred metres. Up valley of these features the only evidence which may indicate active ice is the ridge in the mouth of Coire an Ruadh-stac which may be interpreted as an end moraine. As such it would indicate a readvance during retreat since alternative explanations involving two separate glacial events

are unlikely, the glacier that occupied Strath a Bhathaich being assigned to the Loch Lomond Advance by stratigraphic evidence and no subsequent glacial advances being known in Scotland. However some doubt is cast on the interpretation that the feature is an end moraine by the presence of two other large ridges in the corrie floor that do not resemble end moraines.

The remarkable till accumulation at and down-valley of Area X is situated between the corrie on Beinn Damh and Coire an Ruadh-stac. It seems likely that this may have built up during a period when ice-flow from these two corries converged on this area. This would have occurred as the glacier built up and, perhaps, during retreat. However since the second possibility would not explain groups of parallel ridges on the surface of the till (Robinson p.49 1977) deposition during advance is favoured.

The general pattern of glacier activity in the valley can be summarised as, initial flow towards the valley floor from several sources, followed by increasing importance of ice-accumulation above the upper valley floor resulting in flow out of the area, mainly down-valley but with other outlets over breached watersheds.

6.2 Evidence from a fluted moraine

6.2.1 Introduction

The feature studied is a ridge 400m long and up to 4m high which curves gradually and obliquely across the hillside below Coire nan Cadham. It is the largest and longest of a group of about thirty features: the spacing between the ridges is 15-25m, their heights

range from 1 to 4m and many of them are less than 50m long. The hillside has a gradient of about 10^0 but the features gradually change direction causing the ridge crests to slope at about 7^0 at their upper ends but to become almost horizontal, being almost perpendicular to the slope, at their lower ends. If the line of the longest feature is produced for 200m upslope (to the E) a thick spread mainly composed of angular quartzite boulders is met. In places this constitutes a ridge up to 2m high which runs for a further 200m before being lost in the talus at the foot of the spur between Coire an Ruadh-stac and Coire nan Cadham. This feature is interpreted as being an end moraine.

The association of a large fluted moraine with a mountain spur, and occasionally with a medial moraine, has been observed elsewhere in the field area (Section 9.2.1) Boulton (1978), Eyles and Rogerson (1978) and Boulton and Eyles (1979) suggested that ice convergence behind a spur or nunatak will create a vertical debris septum in the ice linking surficially-derived medial moraine material to a deep englacial concentration. None of these papers considered the likely depositional effects of such a situation when deglaciation occurs.

The fluted moraine was studied for the following reasons.

- (i) To determine the rock-type composition of this feature whose proximal end is 200m down-ice of quartzite bedrock.
- (ii) To search for compositional and textural changes along the length of the feature.
- (iii) To investigate the relationship of the fluted moraine to the medial moraine.

6.2.2 Rock-type proportions

Results from 5 main pits (1-5) dug at 100m intervals along the ridge crest (with Site 1 at the proximal end), were supplemented by stone counts from three pits (A-C) each situated half way between two of the main sites. Table 6.1 shows the results in the context of depth and distance along the ridge.

Table 6.1 Rock-type proportions from the fluted moraine

Site No.	1	2	A	3	B	4	C	5	
Distance (m)	0	100	150	200	250	300	350	400	
		S	59.1			75.5			
		Q	36.4			21.2			<0.5m
		E	4.5			3.3			D
									E
ROCK	S	79.2	77.7	83.4	79.7	77.4	78.2	88.0	87.8
	Q	19.3	20.0	16.6	19.2	21.6	18.3	12.0	10.2
TYPE	E	1.5	2.3	0.0	1.1	1.0	3.5	0.0	2.0
									0.5-0.8m
									T
									H
	S	80.1		82.7		82.6		90.6	
	Q	18.2		17.3		17.4		9.4	0.8-1.1m
	E	1.7		0.0		0.0		0.0	

The results consistently show a high proportion of sandstone in the till. This is remarkable since the proximal end of the ridge is only 200m down-ice of the quartzite outcrop and because the medial moraine that seems to be collinear with the fluted moraine is mainly composed of quartzite.

The clearest trend in the results is that, in all cases, except one, where more than one sample has been taken from one pit there is an increase in the proportion of sandstone and a decrease in the

Fig. 6.2 Cumulative-percentage frequency curves
from the fluted moraine

Sample 1 derived from the proximal end of
the ridge.

Sample 5 derived from the distal end of the
ridge.

proportion of ice-sheet erratics towards the bottom of the pit. The exception is at Site 4 where there is a marginal increase in ice-sheet erratics from the upper to the middle samples. The proportion of quartzite decreases towards the bottom of all the pits.

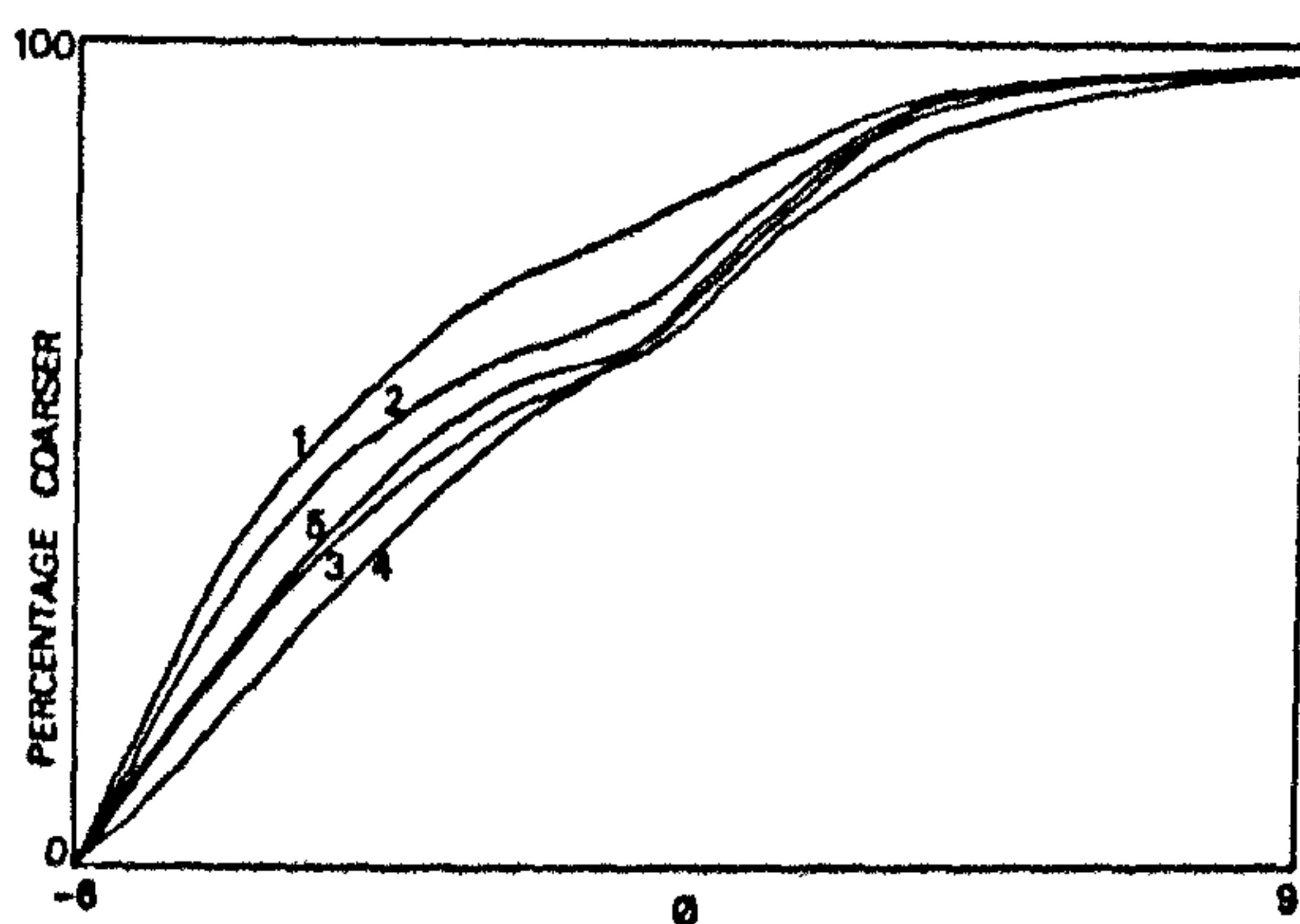
In view of these variations with depth caution must be exercised in suggesting, on the basis of the results from sites C and 5, that the quartzite proportion drops off towards the distal end of the feature. However the apparent 10% reduction (from 20% to 10%) represents a change in the ratio between sandstone and quartzite from 5:1 to 9:1.

6.2.3 Particle-size distributions

Five particle-size distributions were measured, one at each of the main sites. The results are listed in Table 6.2 and shown in Fig.6.2.

Table 6.2 Particle-size distributions from the fluted moraine

Site No.	1	2	3	4	5
Mean Diam.(ϕ)	-2.27	-1.60	-0.87	-0.80	-1.10



There is no significant rank correlation between distance down the flute and mean particle-diameter at the 0.05 level. But the rank correlation does not take account of the magnitude of

changes which are illustrated in the table and figure. These show

that there is a large change along the feature and that only Sample 5 does not conform to this trend. Therefore it is concluded that there is a systematic change in the particle-size distribution of the till along the feature.

6.2.4 clast shape

The mean roundness of sandstone clasts from each of the sites falls in the sub-angular class but the values show no pattern either with depth in the till or with distance along the ridge. The mean roundness of quartzite clasts for each sample is also in the sub-angular class but all the samples, with one exception, are more angular than any of the sandstone samples. Again no pattern was observed either horizontally or vertically.

The highest observed percentage of elongates was 42%. The Mann-Whitney U test showed no significant difference between the sandstone and quartzite samples. All the values are low when considered in the context of the whole project and there is no significant change with depth or distance along the fluted moraine.

6.2.5 Discussion of the results

In the light of the surprising lithological composition of the feature it is proposed that most of the material in it was present before the Loch Lomond Advance. This proposal serves to explain three unexpected results. (i) The high percentage of ice-sheet erratics in the feature. (ii) The high proportion of sandstone

clasts such a short distance down-ice of the quartzite bedrock.
(iii) The contrast between the composition of this feature and the collinear medial moraine.

The proposal implies that the material remained in this area of convergent ice-flow throughout the Loch Lomond Advance during which it was moulded into a fluted moraine but transported only a minimal distance down valley. However the facts that quartzite is relatively more abundant near the surface of the feature and, perhaps, nearer its stoss end indicate that some material was mixed into the till during the event and imply that the fluted moraine is not simply an erosional remnant of pre-existing till.

Fluted moraines have been observed by many authors to have obstructions such as boulders and bedrock humps at their proximal ends (Section 3.3.2). It is suggested that the particle-size distributions observed along the length of this ridge reflect the relatively greater resistance to erosion of coarser till. The subject is discussed in more detail in Sections 7.5 and 10.4.2.

In view of the explanation proposed above it is not surprising that clast form and angularity do not change systematically along the feature since the distance of transport of a clast can have little bearing on its position in the ridge.

The proposal also makes it clear that there can be little relationship between the fluted moraine and the collinear medial moraine.

6.3 Evidence from moraines in Area B

6.3.1 Introduction

A group of fluted moraines runs W into the floor of Strath a Bhathaich from the spur of Maol Chean Dearg that divides Coire an Ruadh-stac from the main valley (Area B, Fig. 6.1). Some of the features are over 100m long and up to 4m high but they are not simple, parallel ridges: many of the crests are broken or breached, there are some minor lateral shifts in the ridges, and in three places a ridge bifurcates to form two features (Fig. 6.3). Despite these imperfections the whole group, viewed across the valley or on aerial photographs, shows a strong lineated pattern accordant with the striae farther E and with the probable direction of ice-movement at the maximum extent of the glacier. Therefore the interpretation that they are fluted moraines is not questioned.

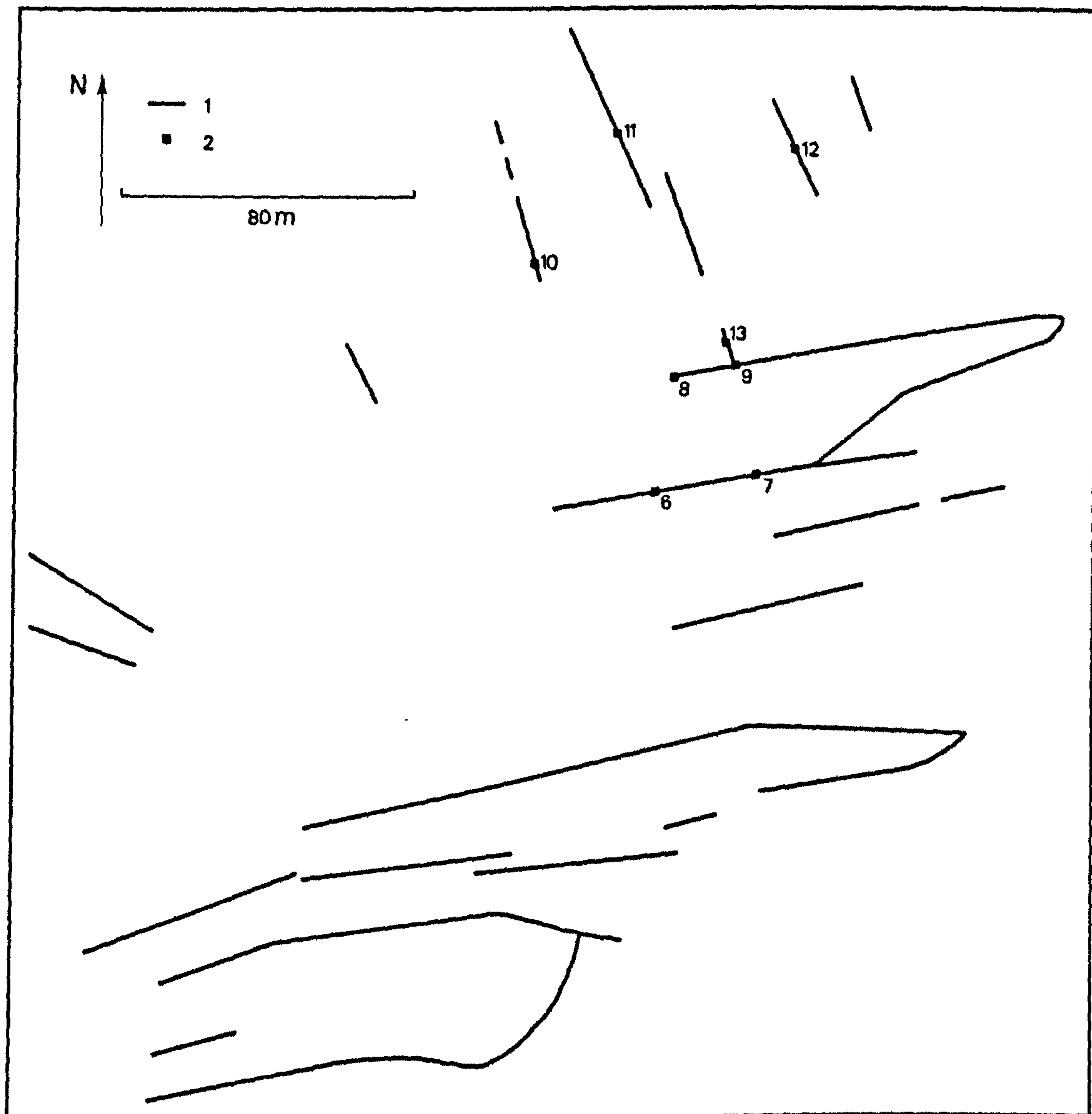
To the N of these features lie some other linear ridges, Fig. 6.3 being a tacheometrically surveyed plan of the crestlines of ridges around the junction of the two groups (cf. Plate 6.1). This is the area in which Robinson suggested that one set of features (the fluted moraines) had been superimposed on another (the ridges). If the two sets of features represent different periods of deposition they clearly have important implications for determining the history of the deposits and for understanding the processes that occur when fluted moraines are formed.

6.3.2 Presentation of the results

The fieldwork described below was undertaken to test the

Fig. 6.3 Tacheometric survey of ridge crests in
Area B

1. Ridge crests
2. Sample sites



suggestion that the features have different ages on the assumption that the characteristics of the till would reflect such differences. Table 6.3A shows the rock-type proportions (calculated from till samples and gravel counts) from different depths in the sites from the fluted moraines as well as mean particle diameters for each of the till samples. Table 6.3B shows the same information for the sites in the ridges. The locations of the sites are given in Fig. 6.3.

Table 6.3A Rock-type proportions and mean particle diameters from the fluted moraines

Site No.	6	7	8	9		
	S	15.5	12.5			
	Q	84.5	87.5		<0.25m	
	E	0.0	0.0			
	S	27.6	30.0	49.5		
	Q	71.7	69.6	49.1	0.25-0.5m	D
ROCK	E	0.7	0.4	1.4		E
						P
TYPE	S	22.5	65.5	47.3	31.7	T
	Q	77.5	33.2	52.0	68.4	0.5-0.75m
	E	0.0	1.3	0.7	0.9	H
	S	29.2	93.4	45.9		
	Q	69.9	6.6	52.9	0.75-1.1m	
	E	0.9	0.0	1.2		
MEAN						
DIAM(Ø)		-1.79	-1.26	-0.34		

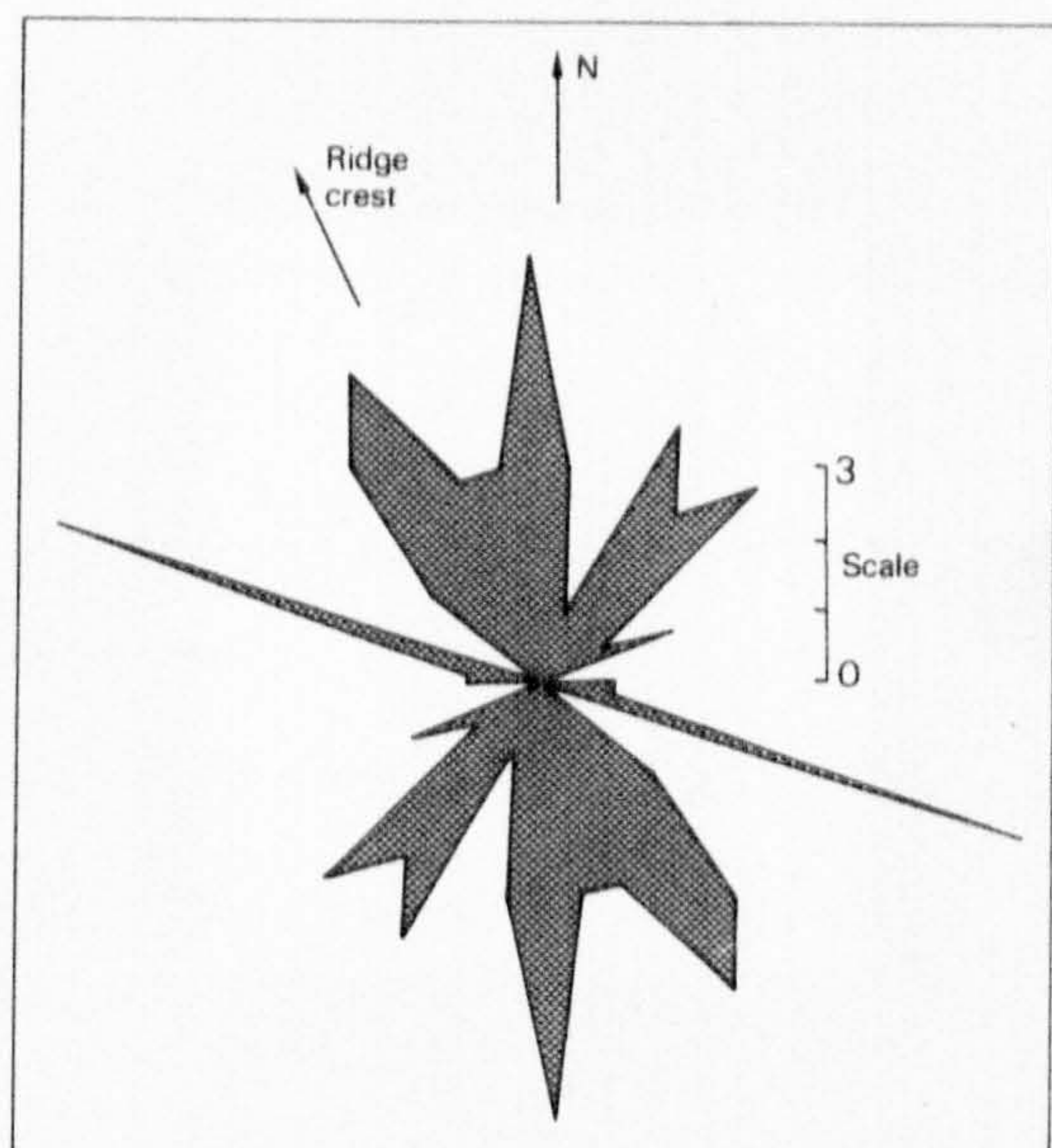
Table 6.3B Rock-type proportions and mean particle diameters from
the ridges

Site No.	10	11	12	13	
	S		33.5		
	Q		66.5	<0.25	
	E		0 0		
	S	34.6	43.1		
	Q	65.4	55.3	0.25-0.5m D	
ROCK	E	0.0	1.6		E
					P
					T
TYPE	S	47.5	23.3	53.8	35.3
	Q	51.5	76.7	43.7	64.7
	E	1.0	0.0	2.5	0.0
					0.5-0.75m H
	S	51.0	26.4	53.6	
	Q	48.5	73.6	45.8	0.75-1.1m
	E	0.5	0.0	0.6	
MEAN					
DIAM(Ø)	0.04	-0.52	-0.84		

Considering all the samples together no general pattern can be observed, either between the two groups or with changes in depth. However, individual sites do show significant changes in composition. Site 7 shows a marked change from quartzite dominance at the surface to sandstone dominance at depth. Sites 10, 11 and 12 show a similar but far weaker trend and are comparatively quartzite-rich at depth, but Site 8 shows a slight increase in quartzite content towards the bottom of the pit. Ice-sheet erratics do not occur in the shallowest samples but they are present in most of the samples from depths greater than 0.25m.

The particle-size distributions do not show a difference between the fluted moraines and the other ridges although the coarsest mean diameters occur at Sites 7 and 8.

Fig 6.4 Till fabric analysis from Site 11



A till-fabric analysis was carried out at Site 11 on the best developed ridge. The clustering is significant at the 0.1 level and the preferred orientation can be seen to be parallel to the ridge-crest (Fig. 6.4).

6.3.3 Discussion of the results

It was hoped that if these two sets of features had been formed at different times or by different processes they would display different characteristics. This is not the case and even the trends of changing composition with changing depth do not serve to differentiate the two groups.

It has been argued elsewhere in this thesis (Section 7.3.4) that till-fabrics parallel to ridge crests indicate that the ridges are a form of fluted moraines. Thus the till-fabric analysis gives limited support to the possibility that the ridges may be the remnants of an earlier set of fluted moraines indicating ice-flow towards the valley bottom up-valley of the large drift accumulation (i.e. towards the NW). This situation might have been the initial result when the glacier from Coire an Ruadh-stac was prevented from flowing directly down-slope by ice from the northern side of the valley.

However, there is no sedimentological evidence to support the

Fig.6.5 Rock-type proportions in samples from
Strath a Bhathaich

1. Sample site
2. Quartzite
3. Streams

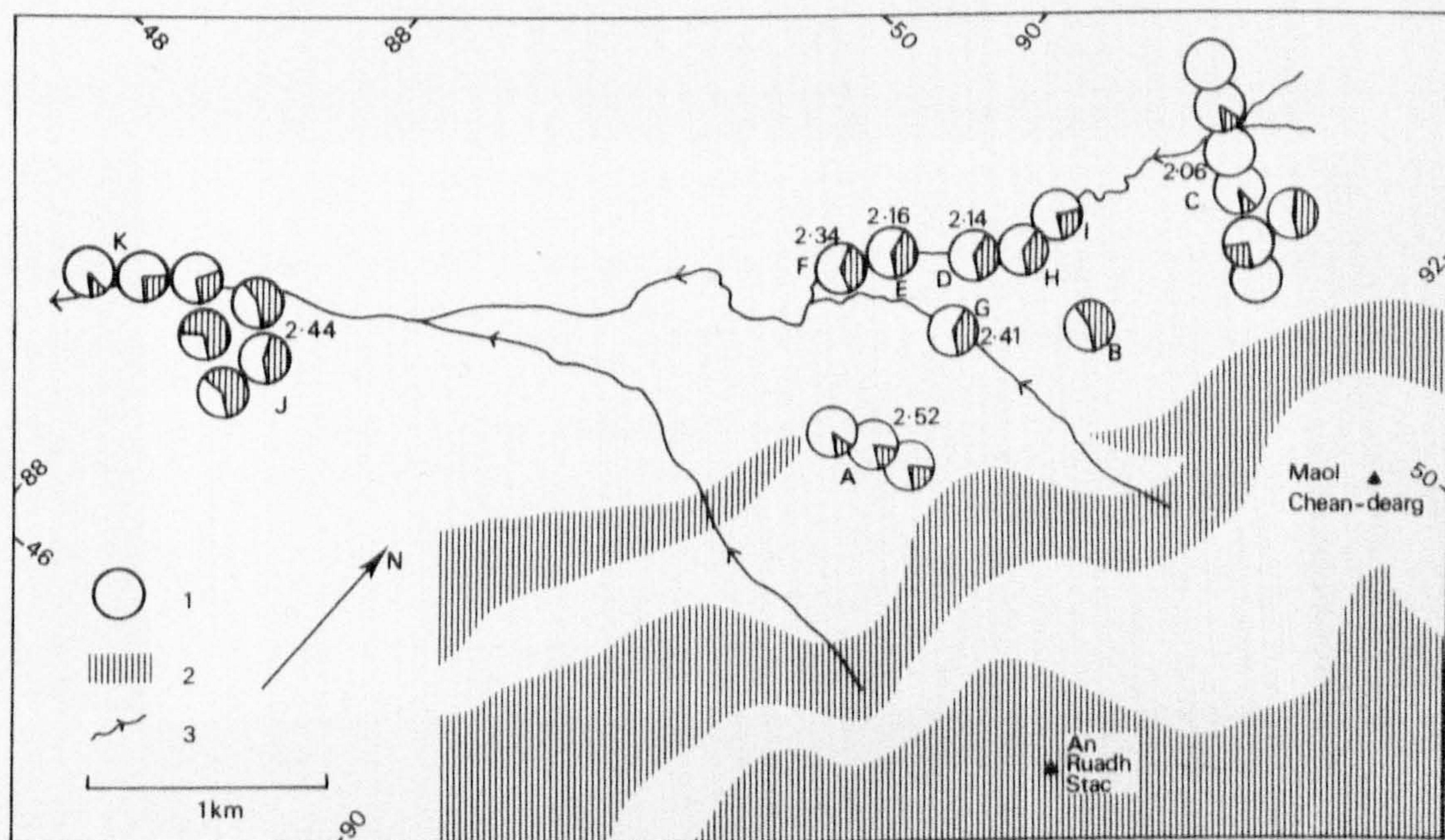
Blank areas in the pie diagrams and in the map represent sandstone. The numbers are mean roundnesses of samples of sandstone clasts.

inference, derived from the morphology, that the fluted moraines post-date the ridges and one weak, ridge-parallel preferred orientation is insufficient evidence for suggesting that the ridges are a form of fluting. Indeed it is difficult to envisage the survival of small ridges adjacent to an area where the fluted moraines testify to active basal flow and moulding of till. Thus no firm conclusions can be drawn.

6.4 Other fieldwork

6.4.1 Introduction

The other fieldwork in this valley was designed to determine the relative importance of different rock-types in the till in



different areas. This aim was facilitated by the presence of five stream-cut sections in the valley (D,E,F,G and H, Fig. 6.5) that allowed samples to be taken at different depths. Elsewhere stone counts were carried out on the crests of the features in pits 0.5m

deep. In addition the mean angularity of samples of sandstone clasts was measured at all these sites.

6.4.2 Presentation of the results

Fig. 6.5 gives generalised results of this work. The groups of sites at A and B have been described in previous sections; in this diagram they have been averaged and shown as three and one pie diagram respectively. Group C is a collection of shallow pits in hummocky moraines across the upper part of the valley. The diagrams at D,E,F,G and H are the results of averaging the measurements from different depths in the till while that at I relates to a shallow pit in the main drift accumulation. Group J comprises five pits dug in the main end moraine, and Group K is made up of the results from two shallow pits 200m and 500m down-valley of the end moraine. The figures beside the pie diagrams are the mean roundness of samples of sandstone clasts. Table 6.4 gives detailed results of the stratigraphic sampling at the five sections.

Table 6.4 Rock-type proportions from sections

Site No.	D	E	F	G	H	
S	62.8	63.8	60.8	67.0	64.1	
Q	37.2	36.2	39.2	33.0	35.4	1m
E	0.0	0.0	0.0	0.0	0.5	
S	65.1	60.7	60.3	64.2	58.2	
Q	34.9	39.3	39.7	35.8	40.7	2m
E	0.0	0.0	0.0	0.0	1.1	
S	63.1	60.6	53.9	56.1	60.8	
Q	36.9	39.4	46.1	43.9	39.2	3m
E	0.0	0.0	0.0	0.0	0.0	
S		60.4		57.4	67.7	
Q		39.6		42.6	32.3	4m
E		0.0		0.0	0.0	
S		57.6		66.9	61.3	
Q		41.6		30.4	38.7	5m
E		0.8		2.7	0.0	
S		55.8		51.3	62.4	
Q		43.7		45.5	37.6	6m
E		0.5		3.2	0.0	
S		52.3		54.9	66.8	
Q		45.7		43.8	32.7	7m
E		2.0		1.3	0.5	
S				55.9		
Q				40.7		8m
E				3.4		

Although the changes with depth are slight they are consistent both within and between most of the sites. In section E there is an unbroken trend of increasing sandstone percentages towards the top of the till. In Section G the same trend is significant at the 0.05 level ($r_s=0.73$), and in Section F it is unbroken but there are only three samples in the section. In Sections D and H there are no such patterns.

Another pattern, displayed in most of the sections, is the absence of ice-sheet erratics in the upper layers of the till. This pattern is in accord with their absence in all the shallow till samples in Group C and most of those in Group J.

It is interesting that Section H breaks both these patterns and that the neighbouring Site I is the only shallow pit (apart from one of those in the end moraine) to have ice-sheet erratics close to the till surface.

One generalisation that can be made from the above table is that the till changes only slightly with depth (the standard deviation of percentages of sandstone in all the samples in the table is 4.56%), suggesting that the samples taken from near the till surface are representative of more than just the surface layers.

6.4.3 Discussion of the results

In the evidence presented in Table 6.4 and Fig. 6.5 there are three sets of information that can be used to infer the source of and relative time of deposition of the debris.

The first relevant set of data is the presence and abundance of ice-sheet erratics in the till. A high percentage of ice-sheet erratics indicates that material that was present in the valley before the Loch Lomond Advance (the majority of which would have been sandstone and quartzite) has not been greatly diluted by material produced during that event, implying that it has not been transported for long distances.

The second set of data is the angularity of clasts in the

material. Only samples of sandstone clasts have been used in Fig. 6.5 because the data for quartzite were not so complete. The interpretation of these data is simply that the farther a clast has travelled the more rounded it will be. However the situation may be complicated by the presence of clasts from ice-sheet till which may be rounded despite having travelled only a short distance during the Loch Lomond Advance.

The third set of data, the percentage of sandstone in the till, is the least easy to interpret. Ice-sheet till would have a high proportion of sandstone since local sources of quartzite in the corries overlooking the valley would be outweighed by the areal predominance of sandstone. At the onset of the Loch Lomond Advance the corries would have contained a great deal of frost-shattered quartzite in the form of talus slopes. Thus the load of the Loch Lomond Advance glaciers would, at first, have been rich in quartzite. As these supplies of frost-shattered debris were exhausted it is possible that sandstone could have regained importance in the till since it crops out over such a wide area.

These ideas can be applied to groups of samples from the valley. Group C has the most angular sandstone clasts indicating short distances of transport; this is also implied by the almost pure sandstone till across the valley except at the foot of Maol Chean Dearg where quartzite dominates. Since this area is up valley of the most important ice sources, and is near the former ice-shed, ice and debris movement are likely to have been slow. The lack of ice-sheet erratics from these sites is only weak evidence because all the samples are taken from shallow pits.

The samples from Area B show a wide range of sandstone and ice-

sheet erratics contents both within and between sites but the combination of a generally high quartzite percentage and the presence of ice-sheet erratics implies that the debris was emplaced early in the Loch Lomond Stadial but not necessarily that the features were formed at that time.

At Sites I and H, situated on the massive till accumulation in the valley floor, ice-sheet erratics are present even at the surface of the till and sandstone percentages are high relative to sections farther down the valley. These observations support the contention that this till was deposited early in the Loch Lomond Stadial (Section 6.2.).

In the sections at D,E,F and G ice-sheet erratics are limited to the lower levels of the till and sandstone does not dominate the till but becomes more abundant towards the surface. These facts indicate gradual deposition over a long period.

The fluted moraine at A has a large proportion of ice-sheet erratics, is dominated by sandstone despite its position a short distance down-ice of quartzite bedrock, and has the most rounded sandstone clasts of any sample in the valley; all of which indicates the presence of a large proportion of ice-sheet till in the feature implying that some material has moved only a short distance during the Loch Lomond Advance.

It can be concluded that almost all the samples dealt with above are lodgement till. In Areas A and B the presence of fluted moraines and ice-sheet erratics proves this to be the case. At Sites I and H the relevant evidence is the presence of ice-sheet erratics at the surface and at Sites E and G the homogeneity of the column of till above till containing ice-sheet erratics suggests that the whole

column was subglacially deposited. Since till at D and F is similar in appearance and composition to that at E and G, the inference can be extended to these sites.

The samples from J, in the main end moraine, are not strictly comparable to the above mentioned sites since an end moraine is not subglacially deposited and will probably contain material that has been transported englacially or supraglacially. The debris at J is coarser than at any other point in this valley where samples were taken. The sandstone clasts are relatively well rounded, ice-sheet erratics are absent and both sandstone and quartzite are well represented.

The samples of ice-sheet till (K) from down-valley of the end moraine contain more sandstone than the end moraine and have an average of 3.7% ice-sheet erratics. If this low value is representative of the till farther up the valley before the Loch Lomond Advance it emphasises the significance of the ice-sheet erratics found in the other samples. For instance the sample from the base of Section G (Table 6.4), containing 3.4% ice-sheet erratics would hardly have been changed by the Loch Lomond Advance.

6.5 Conclusions

It was hoped that the wide variety of features and the close associations between some of them would allow a comprehensive explanation of their deposition and the events of the Loch Lomond Stadial in this valley.

Unfortunately an investigation into the ridges adjacent to the

fluted moraines of Area B was inconclusive (Section 6.3). This meant that the nature of other groups of ridges parallel to one another, such as those at X (Section 6.1.2) became less certain. Therefore it was not possible to make inferences, such as the former direction of ice flow, from them.

The presence of large volumes of debris made adequate sampling difficult but several deep, stream-cut sections revealed fairly homogeneous stratigraphies, allowing confidence to be placed in samples taken from near the surface of the till (Section 6.4.2). Consideration of all the data gathered from a variety of pits and sections provides some explanation of the origin and relative time of deposition of the debris. This explanation was particularly useful in the case of the fluted moraine in area A where deposition of Loch Lomond Advance till would have been incompatible with the high percentage of sandstone found in the feature. The evidence also supports the contention that the massive drift accumulation and impressive bluffs at X (Fig. 6.1) were produced early in the Loch Lomond Advance as a result of ice from the two sources meeting in this area.

In terms of the whole valley it was possible to suggest that much of the till had been deposited early in the Loch Lomond Advance either subglacially or during glacier advance and that, in some places, a large component of the till existed before the onset of that glaciation.

Thus, although interpretation of the morphology of features proved less easy than had been hoped, it was possible to make some generalisations about the mode of deposition and relative ages of the deposits in the valley.

CHAPTER 7

EVIDENCE FROM COIRE A CHEUD CNOIC

7.1. Introduction

7.1.1. Relief and geology

The third area of detailed study is Coire a' Cheud Cnoic (The valley of a hundred hills), which drains into Glen Torridon from the SE (Fig. 7.1). Its SE side is overlooked by four mountains and it is delimited to the south by Meall Dearg (646m). These five peaks are separated from each other by high passes which lead into other drainage basins. The W side of the valley is less well defined because it has been deeply breached. The Abhainn Thraill flows through the breach, capturing much of the drainage from the S and E and leading it away to the SW. Thus the simple image of a valley running from Meall Dearg to Glen Torridon is unrealistic, most of the 'valley floor' being a NW-facing slope leading to two main watercourses close to the base of Seana Mheallan.

The area is composed of sandstone except where thrusting has brought quartzite westwards. Three sub-parallel thrusts, aligned NE-SW, cross the area. One of them traverses Seana Mheallan just W of the summit resulting in a small outcrop of quartzite. A second follows the northern part of the floor of the valley before crossing Meall Dearg and is responsible for a very small outcrop of quartzite just S of Lochan nan Iasgar. Most of the steep ground to the SE of the valley and the floors of the cols on either side of Sgurr nan Lochan Uaine are composed of quartzite associated with a third thrust running through the area.

Fig. 7.1 Coire a Cheud Cnoic

1. Quartzite
2. Hummocky moraines
3. Fluted moraines
4. Striae
5. Inferred glacier limits

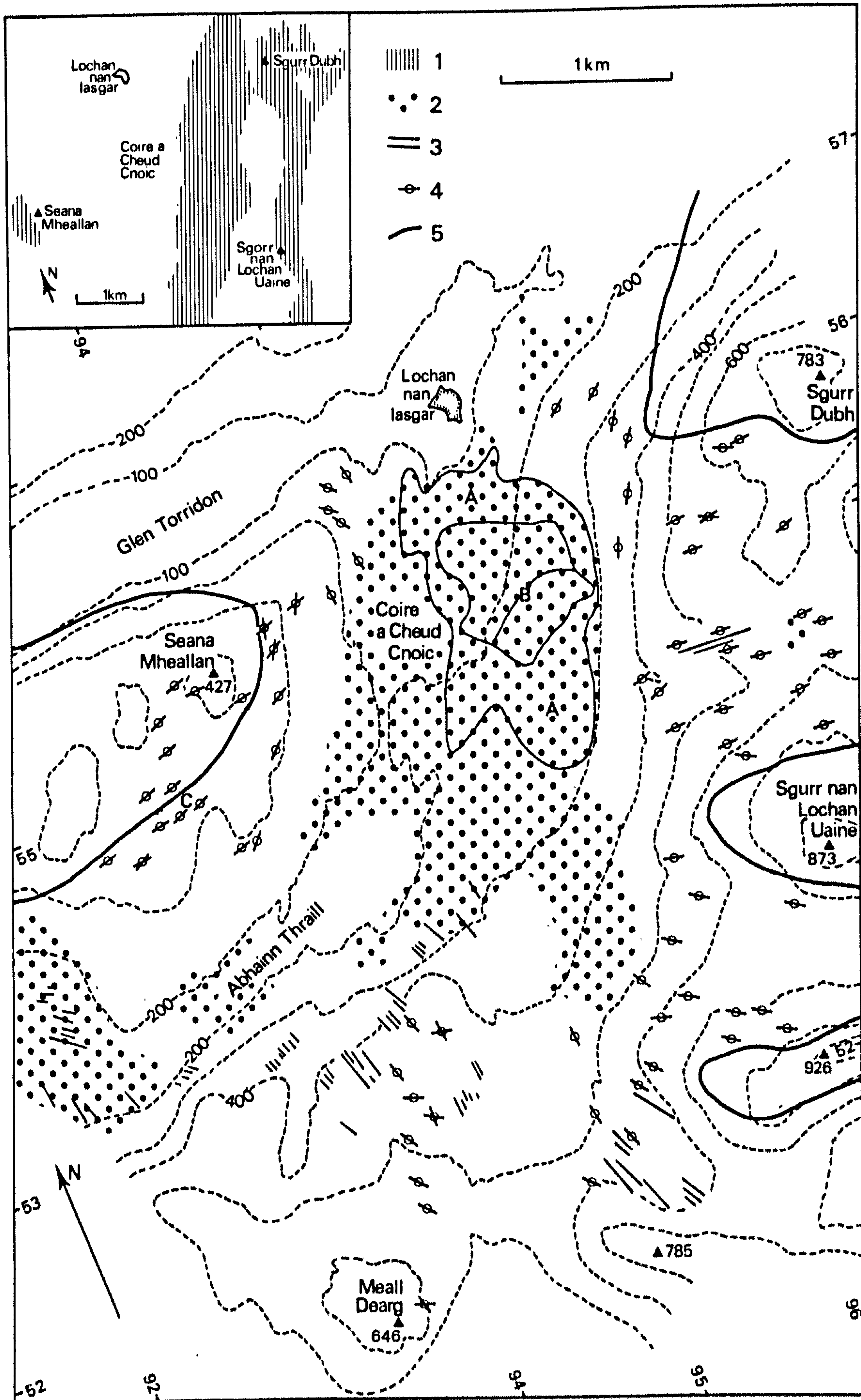


Plate 7.1 Hummocky moraines in Coire a Cheud Cnoic
Viewed from Glen Torridon.

7.1.2 Glacial features of the Loch Lomond Advance

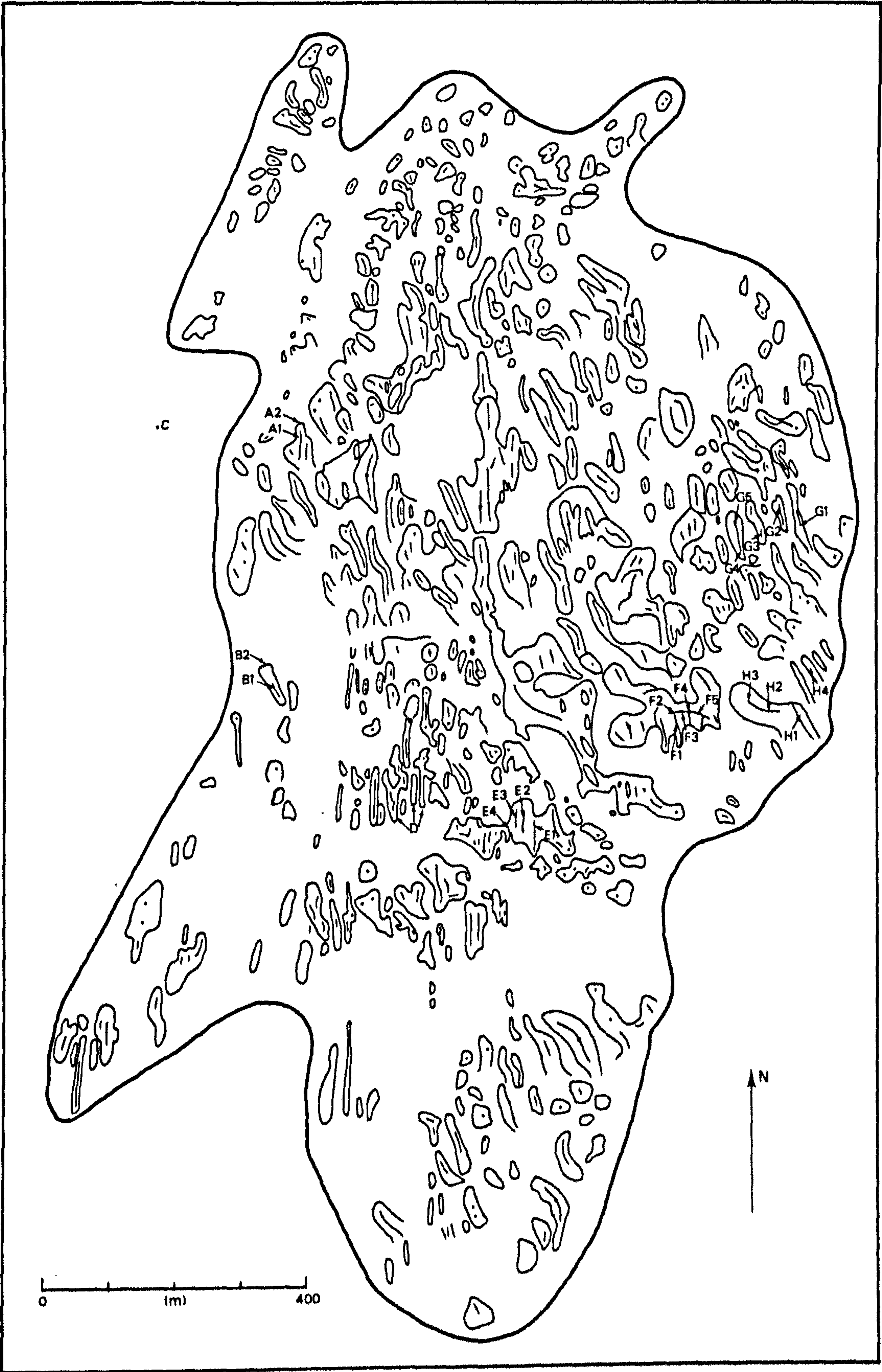
Fig. 7.1 indicates that much of the valley floor is covered by hummocky moraines, and the area of best developed features (A on Fig. 7.1) is mapped in detail (Fig. 7.2). These are the most impressive hummocky moraines described in the project, often reaching 8m in height and having steep sides and sharp crests. Bedrock crops out occasionally between features and often in stream beds indicating that there is no great thickness of till below the hummocks. Some of the features have been used to exemplify Scottish hummocky moraines (Wright 1937 (Plate X), Sissons 1967 (Plate XI.B)) (cf. Plate 7.1).



These pictures illustrate the characteristics listed above and show the mounds to be closely spaced and apparently conical. Thus they appear to be typical results of Eyles' (1978) Facies 1 and Boulton and Eyles' (1979) Facies A2 of sedimentation by a valley glacier.

Fig 7.2 Hummocky moraines in Coire a Cheud Cnoic

The map shows breaks of slopes and ridge crests. It also gives the locations of samples. See Area A in Fig.7.1 for the location of the mapped area.



These models involve thick supraglacial morainic till derived from the hillsides overlooking the glacier, delaying the melting of the glacier so that an area of stagnant buried ice survives in front of an actively retreating glacier. This ice melts chaotically and the supraglacial morainic till is:

"superimposed on the subglacial surface in a form of stagnation or disintegration topography" (Eyles 1978, p.1341).

Robinson (1977) noted that some of the features were elongate, the predominant alignment being S-N, and was thus prompted to suggest that they might be "an abbreviated form of flutings" (p.72). Aerial photographs confirm the presence of many short, straight ridges, running parallel to one another. Clearly the suggestion that these features have been shaped by active ice at the glacier base is incompatible with the initial impression and inferences described above. Most of this chapter is devoted to the presentation of morphological and sedimentological evidence from these features aimed at resolving this problem.

The southern end of the valley is covered by a till sheet which is shown by incised stream courses to be c. 3m deep over much of the area. Its surface is featureless except for two groups of short but well developed fluted moraines. More skeletal flutes occur on thin till in the floor of Coire Grannda and on the steep slopes N of Meall Dearg. Bedrock is exposed over much of the remaining glaciated area, the distribution of striae on Fig. 7.1 being indicative of the area of exposure.

Only two ice-marginal features produced by the glacier have been identified: one is a short ridge on the lower slopes of Sgurr Dubh, and the other an arcuate end-moraine 3km W of Lochan nan

Iasgar.

7.1.3. Glacial events of the Loch Lomond Advance

Robinson's inferred Loch Lomond Advance glacier limits are largely hypothetical owing to the scarcity of ice-marginal features. In addition the complexity of the relief makes speculation about the mode of ice build-up difficult. A large number of striae were mapped in an attempt to solve these problems but the conclusions that can be drawn from this exercise are clouded by the existence of two patterns: the Late Devensian ice-sheet pattern and the Loch Lomond Advance pattern. It has already been stated that the regional flow of the ice-sheet was from the SE but in this area the alignment of Liathach and Glen Torridon from ENE to WSW may have deflected the ice in this direction and other ice-flow directions may have developed during deglaciation (Section 2.5).

The summit of Seana Mheallan is frost-shattered and therefore seems not to have been glaciated during the Loch Lomond Advance. Striae orientated ENE-WSW on this summit constitute evidence for the ice-sheet having flowed in this direction. Hence similarly orientated striae within the area covered by the Loch Lomond Advance, on the NE spur of Seana Mhaellan and on the N slope of Meall Dearg, can also be explained in this way. However, similarly orientated striae at C (Fig. 7.1) are on smooth bedrock and some quartzite erratics from C have been carried to the NE indicating that the Loch Lomond Advance glacier covered this area. It is therefore suggested that here the Advance was more extensive than Robinson showed. It seems likely that striae orientated S-N on the W flank of Sgurr Dubh

were formed by the Loch Lomond Advance glacier.

In and around the cols to the E of the valley the two patterns probably run in the same direction so conclusions are less easy to draw. Robinson considered that ice extended across the northernmost col (S of Sgurr Dubh) on the basis of faint fluted moraines and drift limits. It seems likely that ice also accumulated on the high, undulating ground (above 600m) below the steep upper slopes of the mountain. This extension of the limits would complement the proposed extension on the W flank of Sgurr Dubh. The abrupt start of frost-shattered bedrock on the N slope of Sgurr nan Lochan Uaine also suggests that ice was extensive in the col. In the next col to the S similar observations on the N side of Ben Liath Mhor indicate that ice was more extensive than previously thought in this area. Thus it is concluded that the Loch Lomond Advance ice was generally deeper and more extensive than Robinson surmised but no changes to the essential pattern of ice cover are proposed.

Robinson considered, on the basis of indicators of ice-flow direction, that, at the maximum extent of the Loch Lomond Advance, ice flowed from an ice-cap whose highest part was to the S. The relative importance of different areas in supplying ice to Coire a' Cheud Cnoic at different times was governed by several factors such as firn-line altitude the suitability of accumulation areas and the distance from the accumulation area to the valley. The cols on the E side of the valley are at fairly low altitudes and are not classic ice-sources but a small accumulation in them would result in ice advancing into the valley. The high plateau area to the S is farther from the valley and ice from it would take longer to reach the

valley. However, the evidence (striae, till fabrics and ridge alignments) shows that at the maximal extent of the Loch Lomond Advance the latter source was the more important.

Robinson (1977) and Sissons (1977a) agree that the glacier, at its maximal extent, was confluent with a glacier that flowed into Glen Torridon from the N. The implications of this situation for the behaviour of the glacier are considered later in this chapter.

7.2. Fieldwork design

7.2.1. Objectives

The depositional features towards the mouth of Coire a' Cheud Cnoic merit close examination because they are outstandingly developed features and pose considerable problems of genesis. Thus a large fieldwork effort was directed towards answering the following questions.

- (i) Are there fluted moraines in the area?
- (ii) If they occur are they isolated, exceptional features?
- (iii) How much of the debris was derived from the quartzite ridge to the E of the valley?
- (iv) Did this debris fall onto the surface of the ice or was it entrained subglacially?
- (v) How are quartzite and sandstone debris distributed relative to one another?
- (vi) Does the debris change, compositionally or texturally, from feature to feature?
- (vii) Does the debris change, compositionally or texturally,

from group of features to group of features?

(viii) Does the composition of the debris change with depth?

(ix) Is the material subglacial till, supraglacial till, fluvioglacial debris or a mixture of these?

(x) How does it compare with other sediments sampled in the project?

7.2.2. Problems

Fieldwork in this valley was faced with two problems. The first was that the steep sides and sharp crests of the features suggested that post-depositional slumping may have occurred; thus most samples were taken from the crests of the mounds because these are the positions least likely to have been modified. Samples were taken from intervening hollows only when small features were being investigated. The second problem was that the scale of some of the features is so large that samples taken from pits 1m deep may not have been representative. Some precautions were taken to assess this possibility. Firstly, in two places where a stream had eaten into the base of a feature the crest and the base of the feature were sampled and the results compared. Secondly, samples were always taken from groups of neighbouring features so that the reproducibility within a group indicated the representativeness of the samples. Thirdly, stone counts at small vertical intervals, down to a depth of 1.1m in most of the pits, were used to test for significant changes in composition through this part of the features.

In this context it is relevant that if slumping has been

important then some of the samples taken from near the present surface of the features were originally situated at some depth within them.

7.3. Evidence from the whole valley

The results of some of the techniques employed are best presented in the context of findings from the whole valley before detailed case studies are reported (Section 7.4).

7.3.1. Deep till samples

The valley has only three small sections cut in drift. These provided samples of material from deep in the features to compare with samples from pits dug in their crests. The results of five samples from three locations (A, B and C, Fig. 7.2) are summarised below.

Table 7.1. Data from areas A, B and C

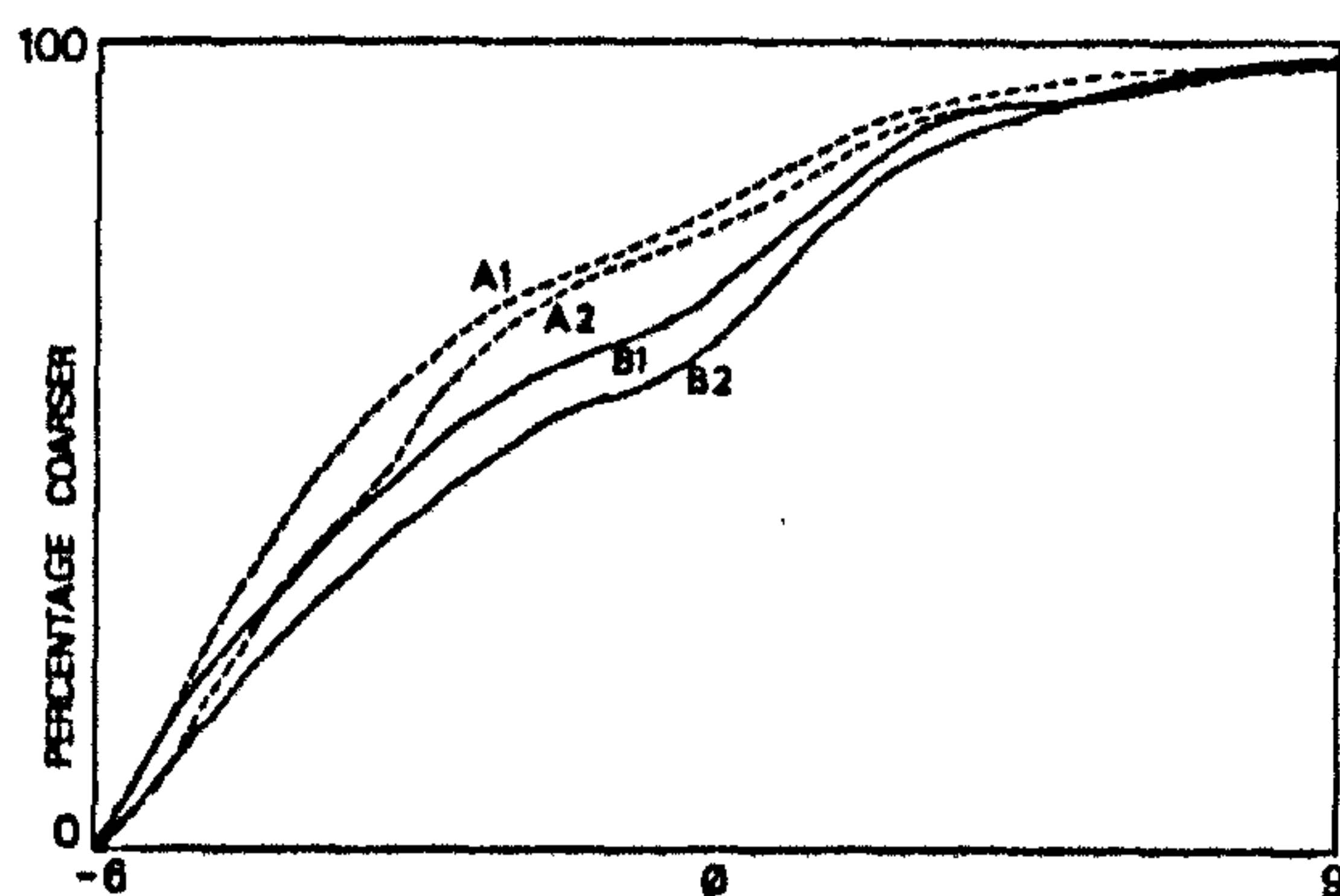
Site	Sandstone form	Sandstone roundness	Composition (%) sandstone quartzite erratics			Mean diameter
A1	20	2.80	76.2	8.5	15.3	-1.84
A2	34	1.34	99.6	0.0	0.4	-1.27
B1	12	2.64	93.2	4.1	2.7	-0.88
B2	20	2.28	97.4	2.0	0.6	-0.35
C	22	2.08	80.4	7.0	12.6	-0.66

In this and other tables clast shape figures denote the percentage of elongates; roundness figures are the means from samples of 25 or 50 clasts, individual scores ranging from 1 (very angular) to 5 (very rounded) and mean diameter is measured in phi units.

Fig. 7.3 Cumulative-percentage frequency curves
from samples at A and B

A1 was taken from the crest of a hummocky moraine and A2 came from a small section 7m lower down and 15m away from the upper site. A2 is 2m higher than a near-by horizontal slab of bedrock exposed in the stream bed. B2 is also taken from the base of a hummock, B1 coming from its summit. Bedrock does crop out near to B2 but in this case its surface slopes so steeply that it is difficult to estimate the depth of the till underlying the sample. C was taken from 3m below the till surface at a shallow section in a subdued hummock.

Both the pairs of samples (A and B) show a similar pattern of changes. In each case the lower sample has more elongate and angular sandstone clasts, lower proportions of quartzite and ice-sheet erratics and slightly finer mean particle diameters. All these characteristics indicate that the debris near the bases of the hummocks has more local origins than that near their crests. Subsidiary observations made at A2, that support these findings, are that two clasts have slickensides on their surfaces and that all the sandstone clasts have similar colour and grain size, indicating that the stones were not derived from widely dispersed sources.



The prevalence of local debris at depth is not unexpected but the fact that the magnitude of the changes from the top to the bottom of the till are small shows that the samples from near

the surface are not unrepresentative. This is a particularly important result in respect of the particle-size analysis because it might be suggested that in this wet climate the till at a depth of 1m

would have been modified by washing out of silt and clay. Fig. 7.3 gives the cumulative-percentage, frequency curves of the four samples and shows that the differences between members of the same pair of samples are small. The sample from location C is also interesting because, coming from a depth of 3m it has more in common with the upper sites from A and B than with the lower sites: notably high quartzite and ice-sheet erratics contents. This, again, indicates that samples taken from shallow pits are representative of till at greater depth.

These results are also relevant to the question of whether or not the debris has been deposited from a supraglacial position. The strong indications that the till at the bases of the features has been very locally derived appear to rule out the possibility that it has ever been carried far above the ground surface and the similarities, especially in particle-size distributions, between it and the till at the tops of the features make it difficult to envisage them having had greatly different origins. Therefore it seems unlikely that the till near the surface of the features has been carried at the surface of the glacier.

7.3.2. Slopes

At each of twenty locations scattered through the area of hummocky moraines the gradients of the steepest ten slopes were measured using an Abney level. The slopes of the features typically have a long section of constant gradient between the crest and the base and it was this part of the slopes that was measured. This work was partly for descriptive purposes and partly to see whether there

is a sharply defined limit to slope steepness, which might suggest that subaerial agencies have been important in modelling the features. The steepest slope measured was 39° , subsequent scores being 6 at 38° , 8 at 37° , 18 at 36° , 17 at 35° , 24 at 34° , 16 at 33° , 15 at 32° , 30 at 31° , 14 at 30° . (This last low score shows that slopes of this and lower gradients were less likely to be measured). It can be seen from these results that there is no well defined limit to slope steepness but this does not, itself, show that subaerial processes were not important because the variability of steepness may reflect differences in the physical properties of the materials of which the slopes are composed.

7.3.3 Gravel counts

Another piece of work that is best presented for the valley as a whole is the sampling, at 10-15cm vertical intervals, of the gravel fractions to determine the relative abundance of different rock types in the pits. This was carried out to depths of 1m or 1.1m at 32 sites and Spearman's rank correlation coefficient was used to test the significance of the results. The sites showing significant results are listed below (Table 7.2) together with the type of change and the range of values from bottom to top.

Table 7.2 Significant changes in rock type composition.

Site	Trend	Range (% sandstone)	p	Converse trend (if not quartzite)	Range (% erratics)	p
D3	T-	65-55	0.05			
D4	T-	60-40	0.05			
D5	T-	90-60	0.05			
D8	T+	50-70	0.05			
E2	T-	74-42	0.01			
F1	T-	90-60	0.01			
F3	T+	30-99	0.01	E-	67-0	0.01
F4	T+	75-91	0.01	E-	12-0	0.01
F5				E-	6-0	0.01
G2	T-	70-50	0.05			
H1	T+	3-19	0.01			
H2	T+	6-89	0.01			
H3	T-	95-20	0.01			

T- means a decrease in sandstone towards the surface of the till and always corresponds to an increase in quartzite.

T+ means an increase in sandstone towards the surface of the till.

E- means a decrease in ice-sheet erratics towards the surface of the till.

The nineteen sites not listed in the table did not display significant changes in composition over this depth range.

With the exception of area H, which will be considered later, there is only one site (D8) where sandstone increases as quartzite decreases towards the surface (In F3 and F4 the sandstone rise relates to a drop in the proportion of ice-sheet erratics.) Thus if any pattern can be discerned from the significant trends it is a decrease in sandstone concentration towards the surface, which is consistent with the results of the sampling described in section 7.3.1. However the lack of significant trends in the majority of the samples means that the more important conclusion is that no strong pattern emerges.

7.3.4. Till-fabric analysis

Till fabrics trending parallel to the crests of fluted moraines

have been observed by several authors (Gravenor and Meneley 1957, Shaw and Freshauf 1973, Boulton 1976, Lawson 1976). In this valley a possible explanation of the ridges is that they may be the result of crevasse filling, either by material falling from the surface of wasting ice or being squeezed up from its base. Squeezing would tend to yield preferred orientations transverse to the ridge crests (Hoppe 1952) and slumping would probably yield no pattern. Whereas, the occurrence of ridge-parallel orientation modes not only supports the fluted moraine hypothesis but also excludes these alternative explanations. The results are summarised below and in Fig. 7.4.

Table 7.3 Results of till-fabric analyses

Site	Position	Orientation modes w.r.t. crests			$A_n 180^\circ$ p	
		parallel	transverse	oblique		
D1	R	X			2.4839	0.001
D1E	R				0.1144	
D1W	R	X		x		
D2	R			X	1.5814	0.001
D3	R				0.1137	
D5	S	X	x			
D6	R			X	1.1967	0.05
D7	S	X			1.6115	0.001
D8	S	x		X		
E2	R	X			1.1828	0.005
E3	R	X			1.8278	0.001
E4	R	x		x		
F1	R	x	x			
F3	S	X	x			
F4	R			xx		
F5	S	X			0.9094	0.025
G1	R	X			0.7356	0.05
G2	R	X			0.700	0.05
G3	R	x		X		
G4	R			xx		

w.r.t. means with respect to.

R means the site is in a ridge.

S means the site is in a swale.

X denotes the preferred orientation.

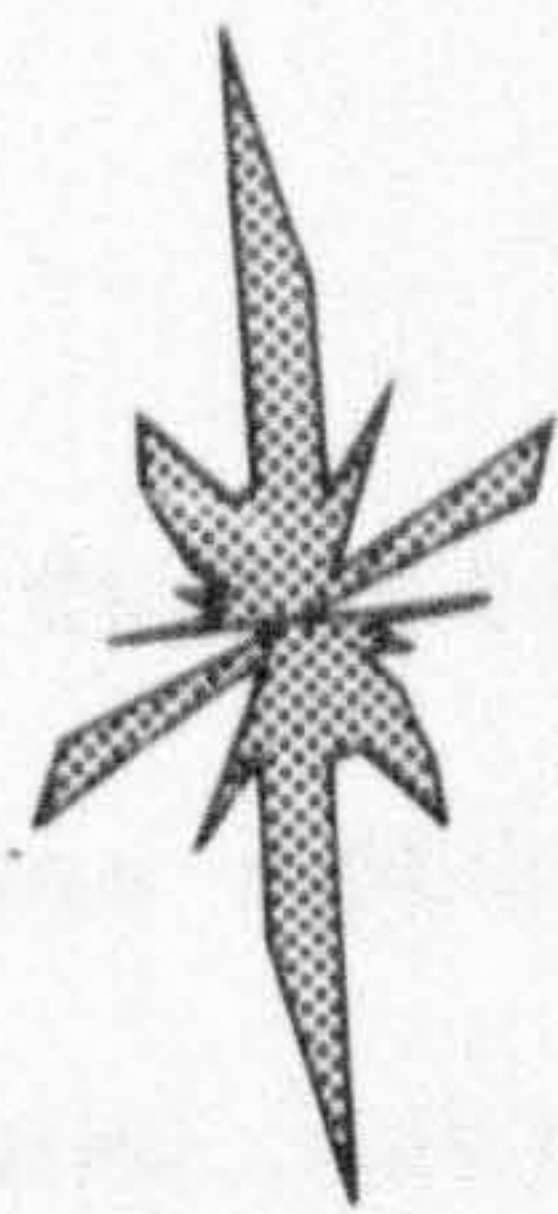
x denotes secondary trends or one of two, equally important, modes.

An. 180 values and significances are given for those samples that are not bimodal.

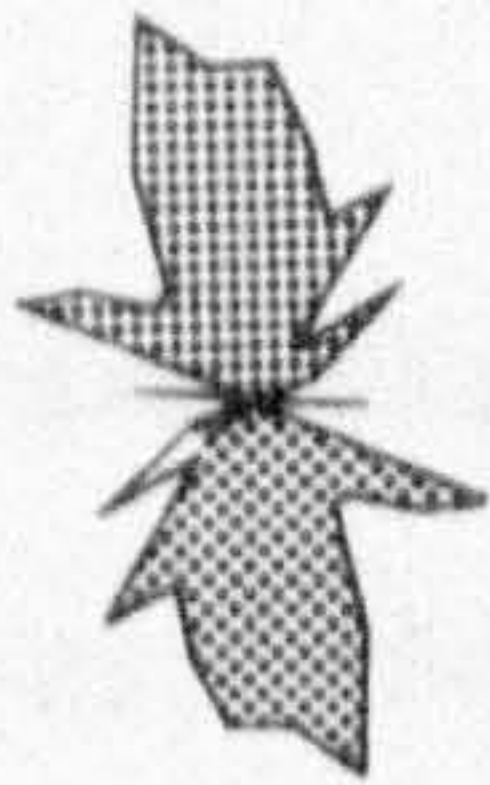
D1 E and W are on either side of the ridge close to D1.

Fig. 7.4 Till fabric analyses from Coire a Cheud Cnoic

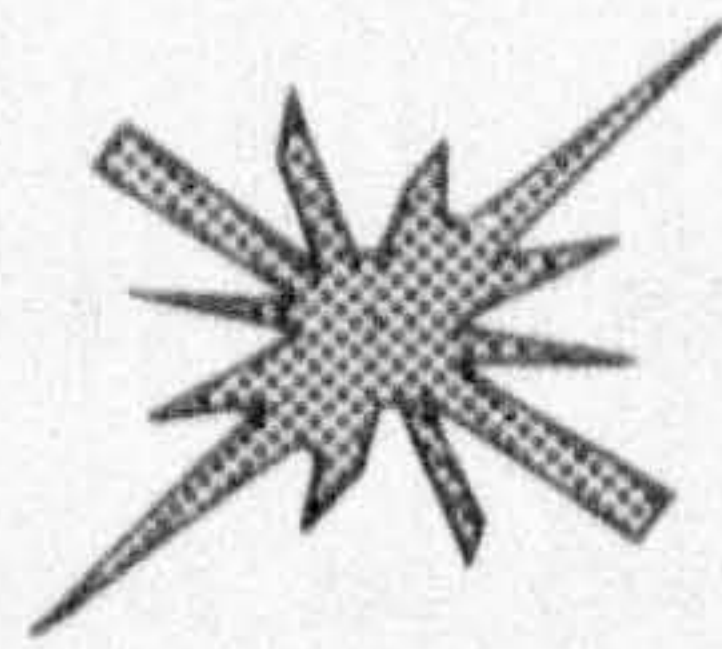
Ridge crest orientations are parallel to the long axis of the page. See Table 7.3 for details.



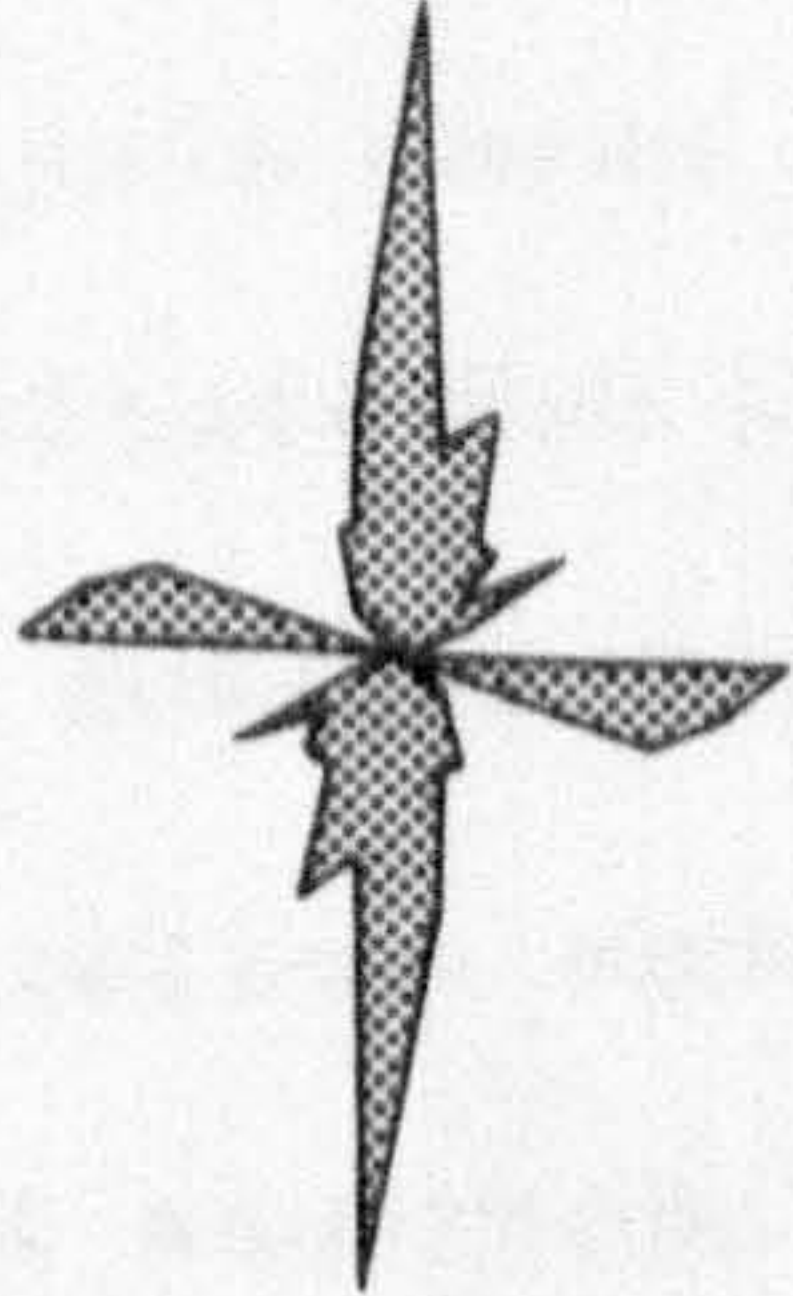
D1W



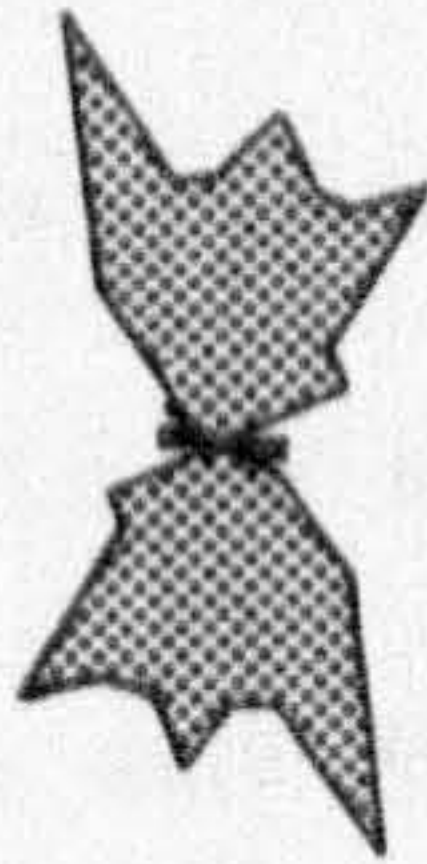
D1



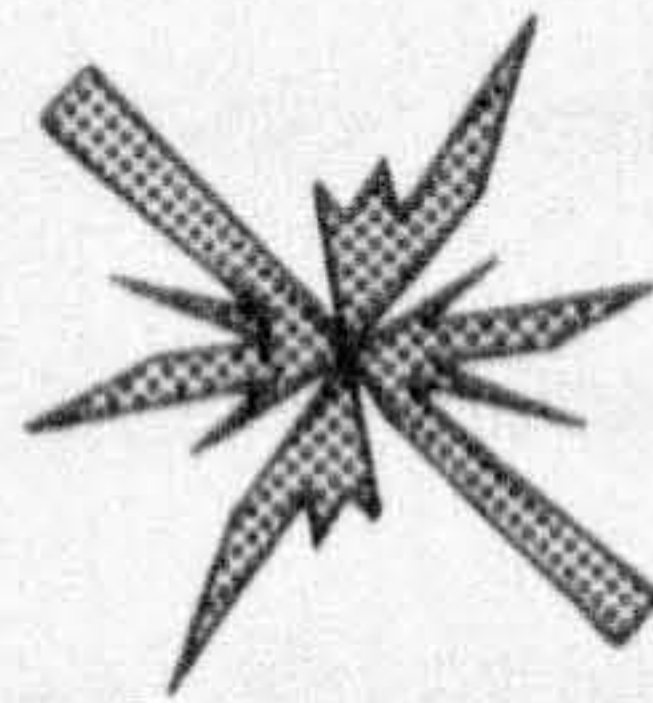
D1E



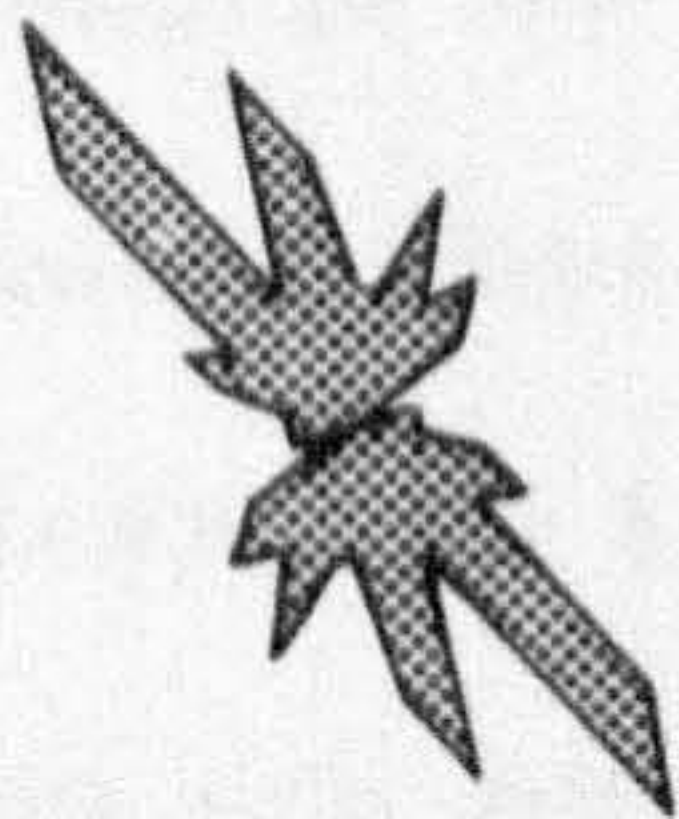
D5



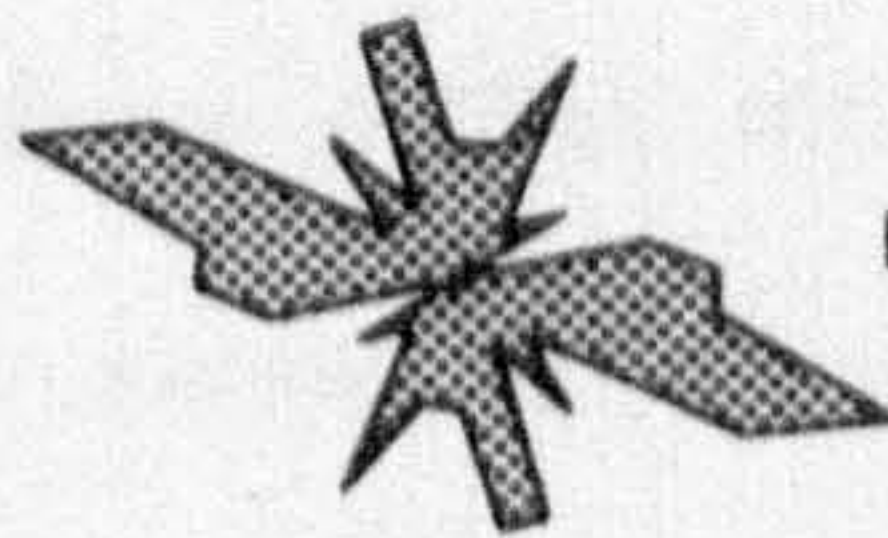
D7



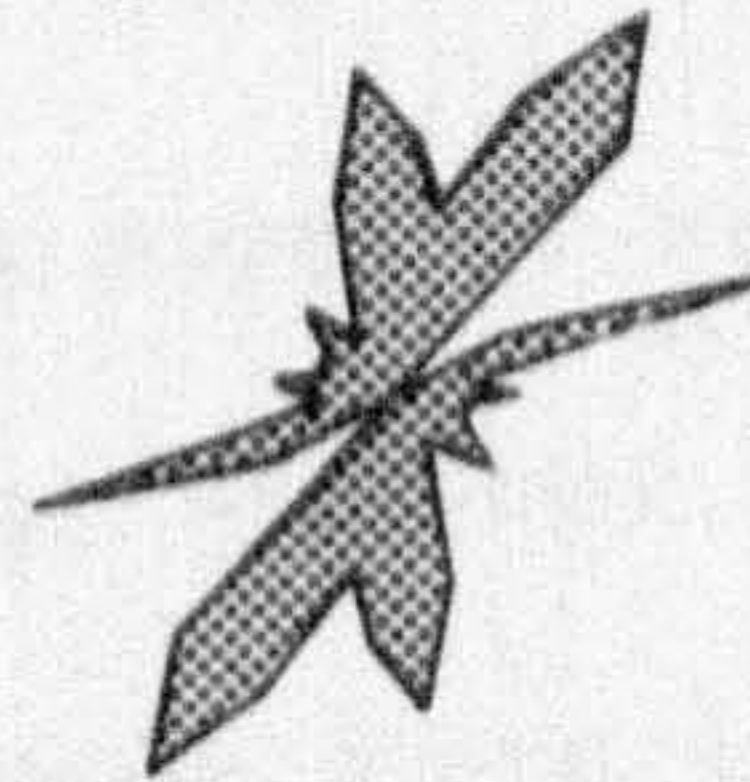
D3



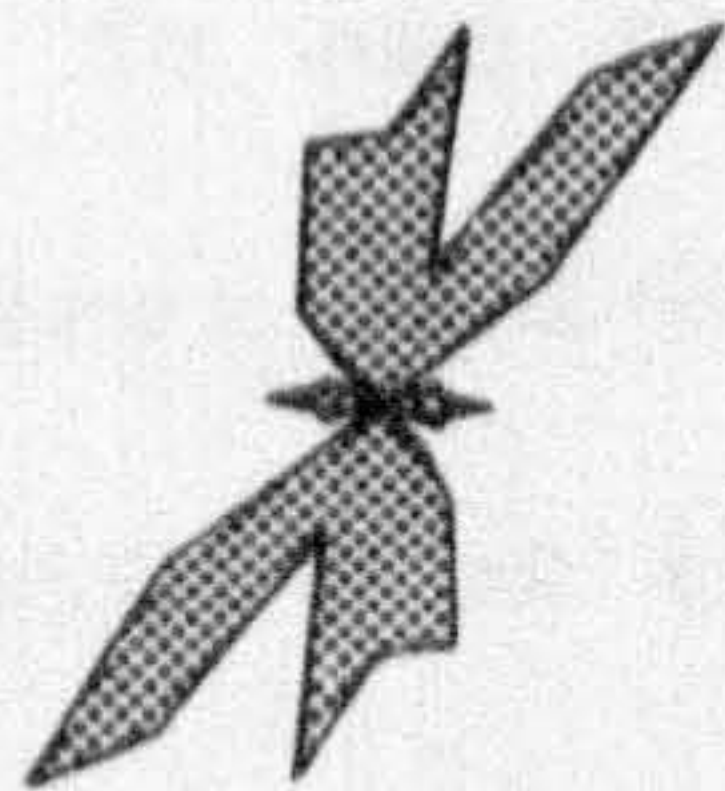
D6



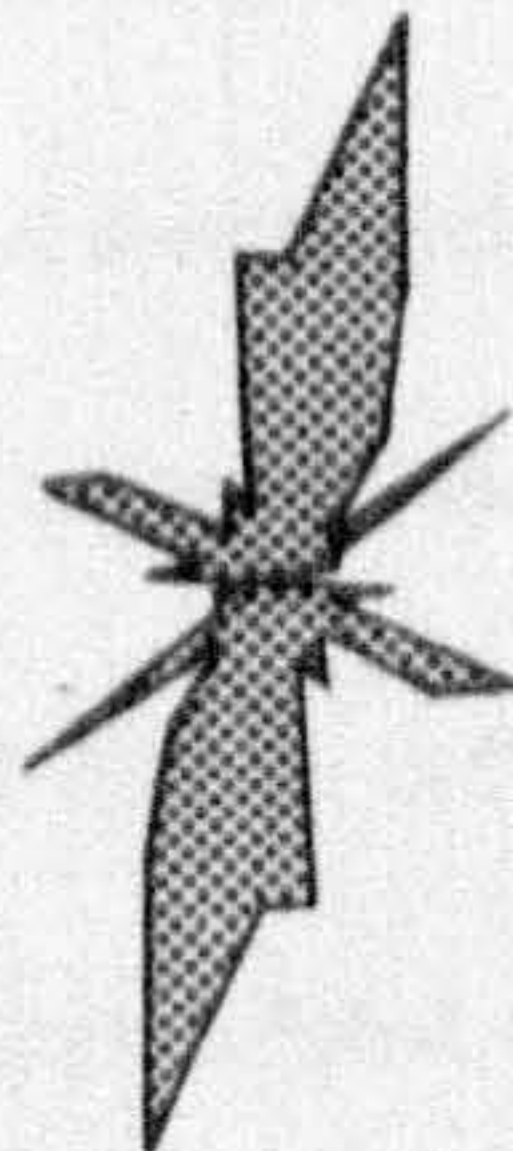
D2



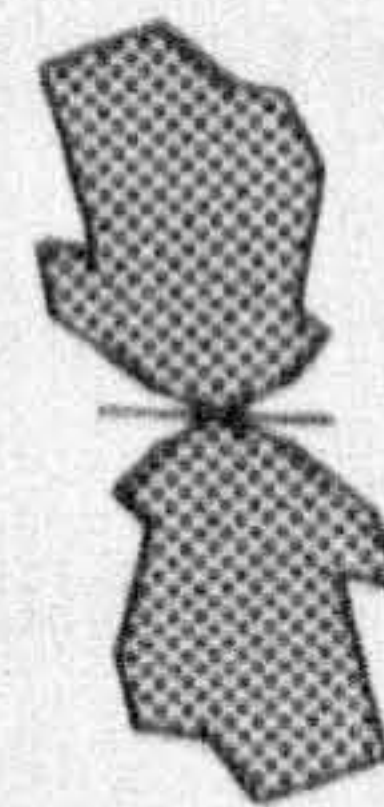
D8



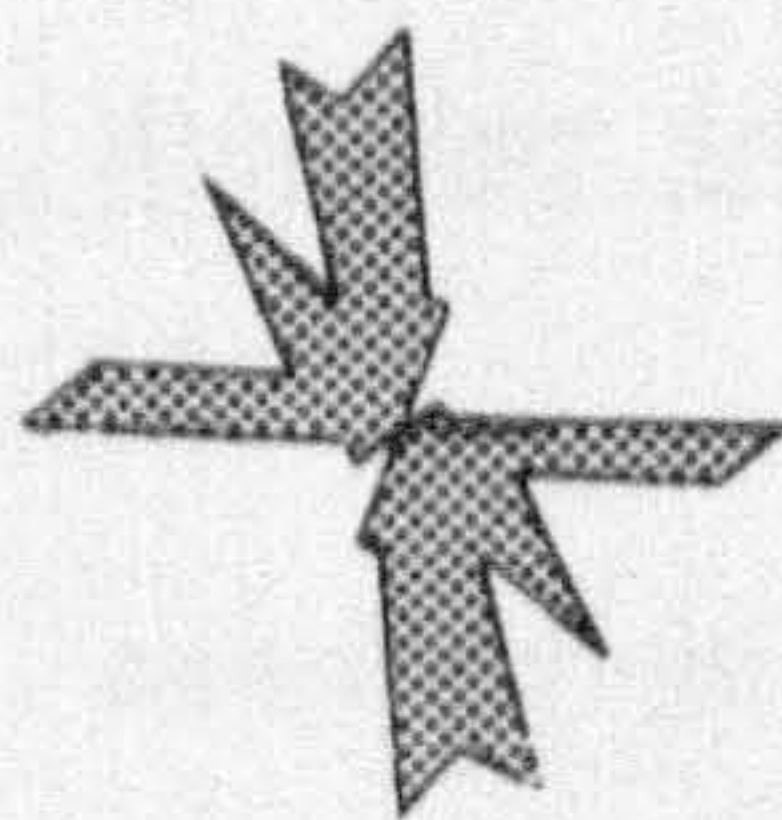
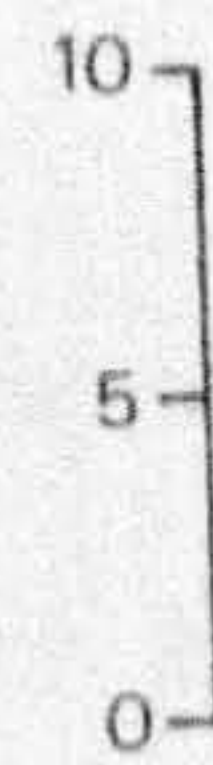
E4



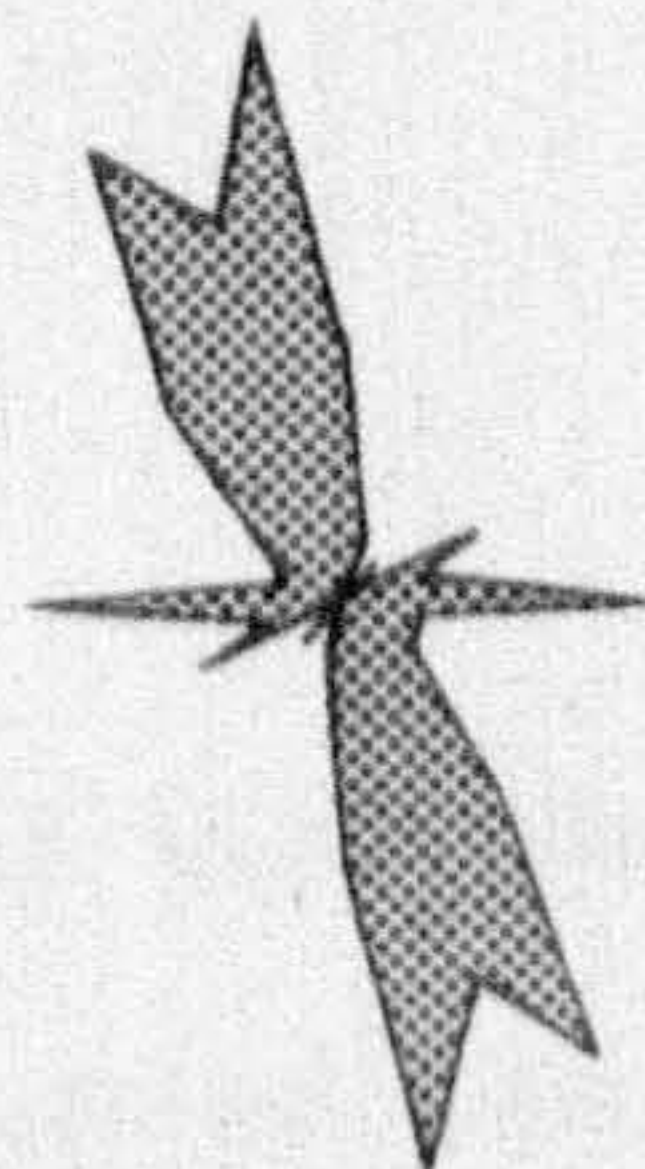
E2



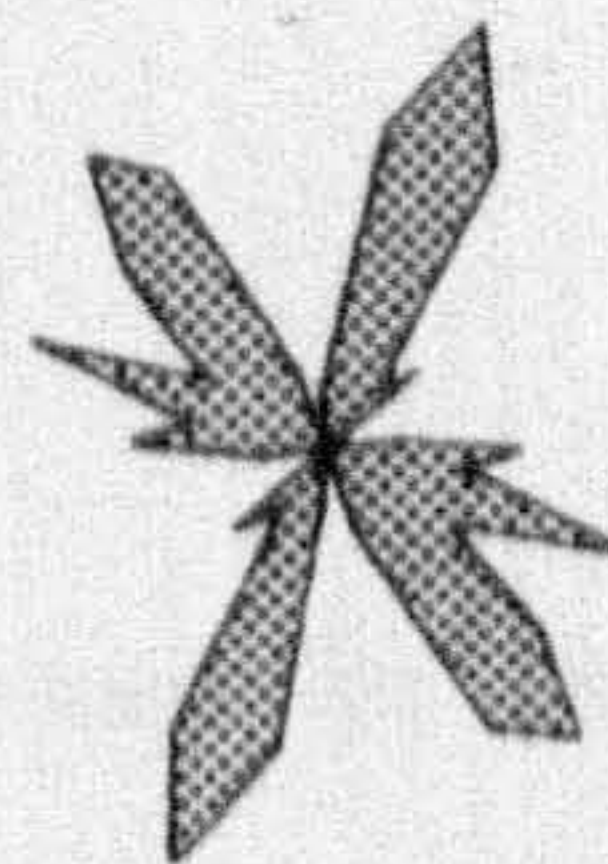
E3



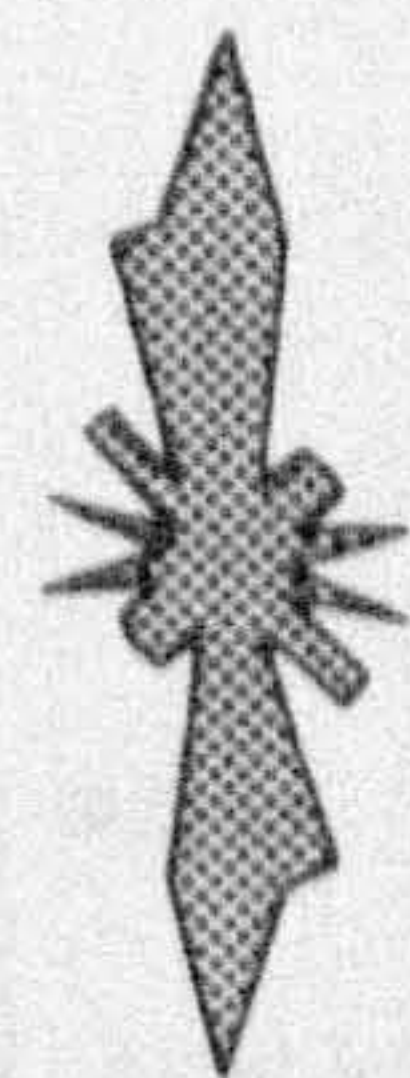
F1



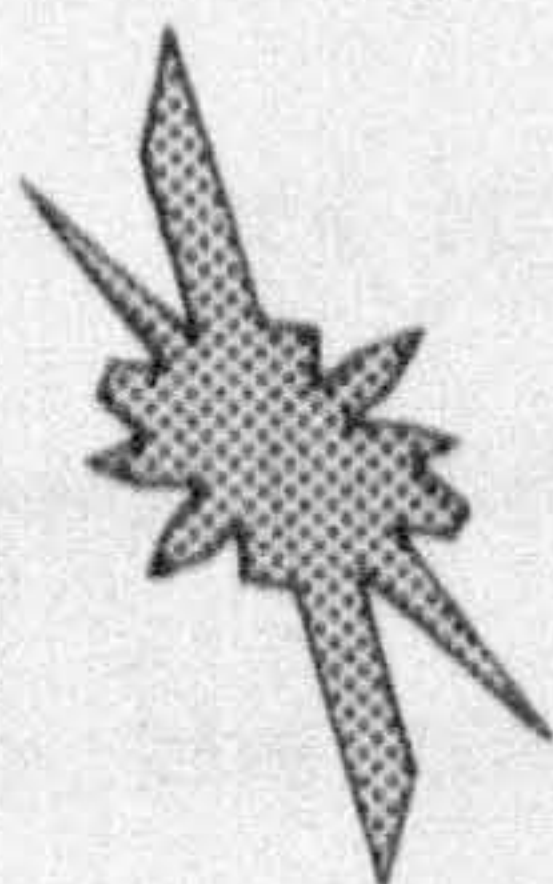
F3



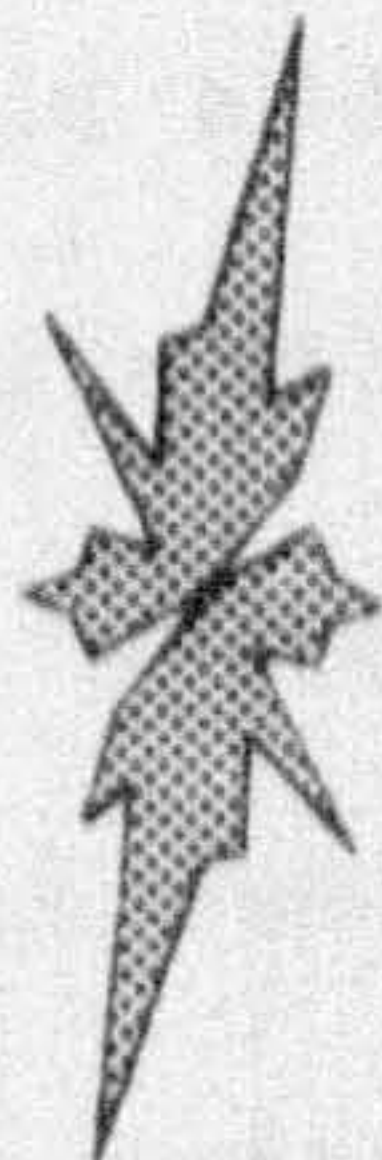
F4



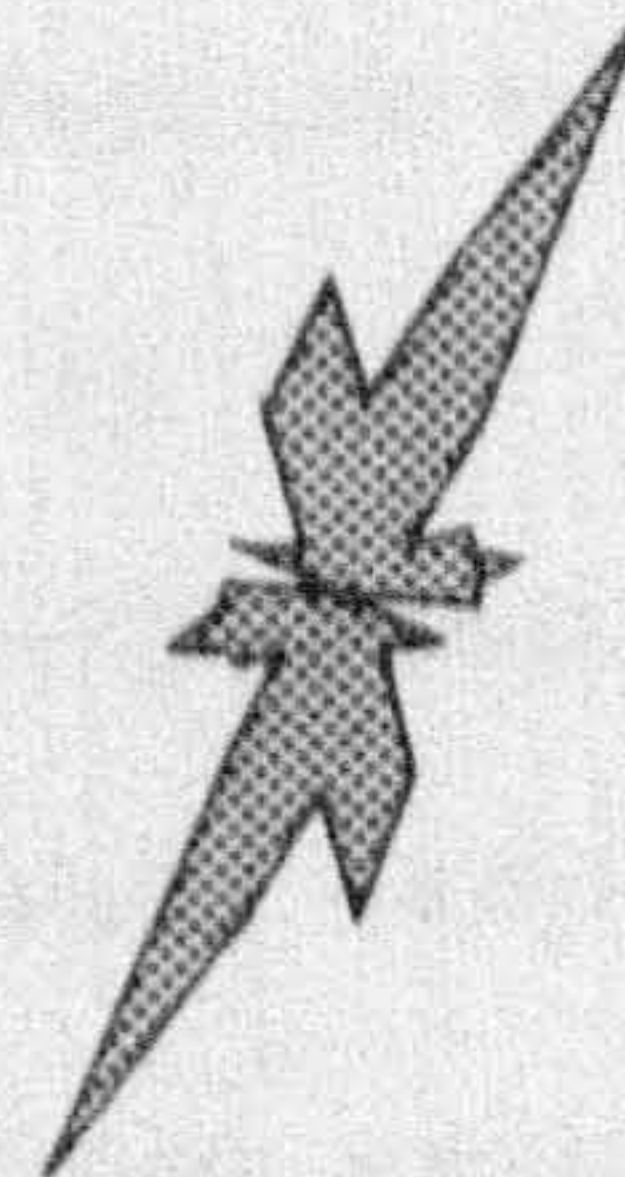
F5



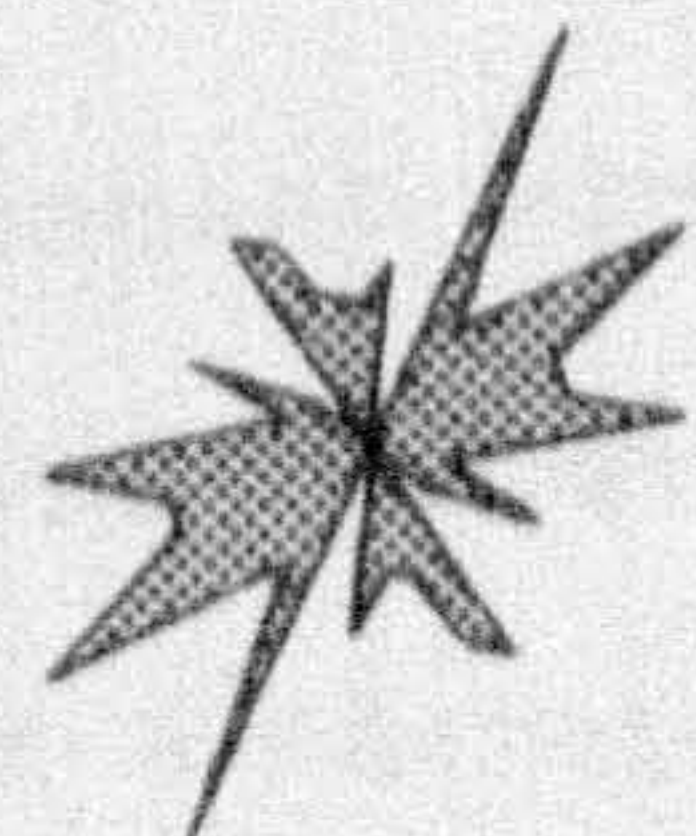
G1



G2



G3



G4

The Table (7.3) and Figure (7.4) show that ten of the twenty analyses exhibit primary modes parallel to the ridge crests and two of these have a secondary transverse peak. In another case the analysis shows parallel and transverse modes of roughly the same magnitude but a transverse mode is never dominant. Four fabrics show dominant modes oblique to the ridge crests while two others have two oblique modes each and another has oblique and parallel modes of equal magnitude. Only two analyses fail to display any modes. Thus the results do not support either of the crevasse-filling mechanisms mentioned above. They offer strong support to the suggestion that the features are a form of fluting. However the results from the swales are more consistent than those from the ridges as will be shown in subsequent sections

It can also be concluded that the results give independent evidence of S-N ice-flow along the valley at or after the time of deposition of the features and, therefore, rule out the possibility that the debris was deposited from the surface of wasting ice.

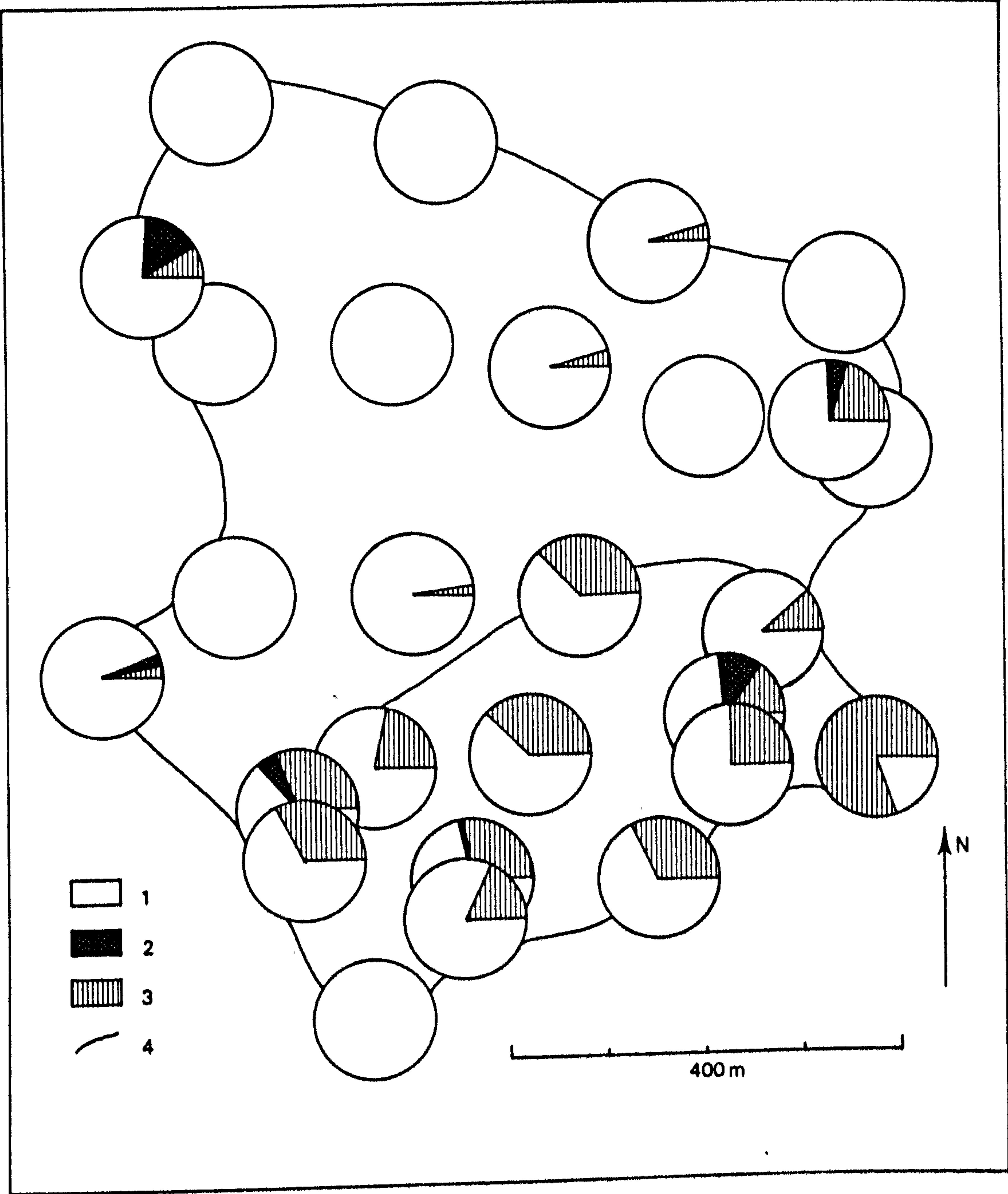
7.3.5. Boulder counts

Another piece of work that relates to the valley as a whole is the counting of a hundred boulders at each of twenty locations to determine the abundance and distribution of quartzite debris. The results are shown in pie diagrams on Fig. 7.5 together with the averaged results from groups of till samples. The differences between the two types of results reflect sampling of different size fractions (no ice-sheet erratic boulders were found in this valley)

Fig. 7.5 Pie diagrams of rock-type proportions in
Coire a Cheud Cnoic

1. Sandstone
2. Ice-sheet erratics
3. Quartzite
4. Area limits (see Fig. 7.1)

The results are derived from counts of surface boulders and from groups of till samples. The area is subdivided on the basis of sites with a relatively high proportion of quartzite.



and, perhaps, the different stratigraphic positions of the samples. The most important finding is that quartzite accounts for only a small proportion of the surface boulders. Since all the steep ground overlooking the valley is composed of quartzite and since supraglacial debris is characteristically bouldery and should be best represented at the surface of the till it can be concluded that supraglacial debris, derived from the valley sides, does not constitute an important part of the accumulated material in the valley.

Inspection of the pattern of results shows that the highest quartzite contents occur in the S and SE parts of the area. This is unexpected because, with S-N ice-flow in Coire a Cheud Cnoic any quartzite contribution, either as the load of glaciers entering the valley from the E, or as rock-wall debris, would be streamed northwards along the E side of the valley. The quartzite-rich samples are situated below the mouth of the col between Sgurr Dubh and Sgurr nan Lochan Uaine so it can be tentatively suggested that the pattern reflects ice-flow down from this col at a time before it was deflected by stronger ice-flow in the main valley. Such a time may have occurred during the ice-sheet glaciation or early in the Loch Lomond Advance.

7.3.7. Summary

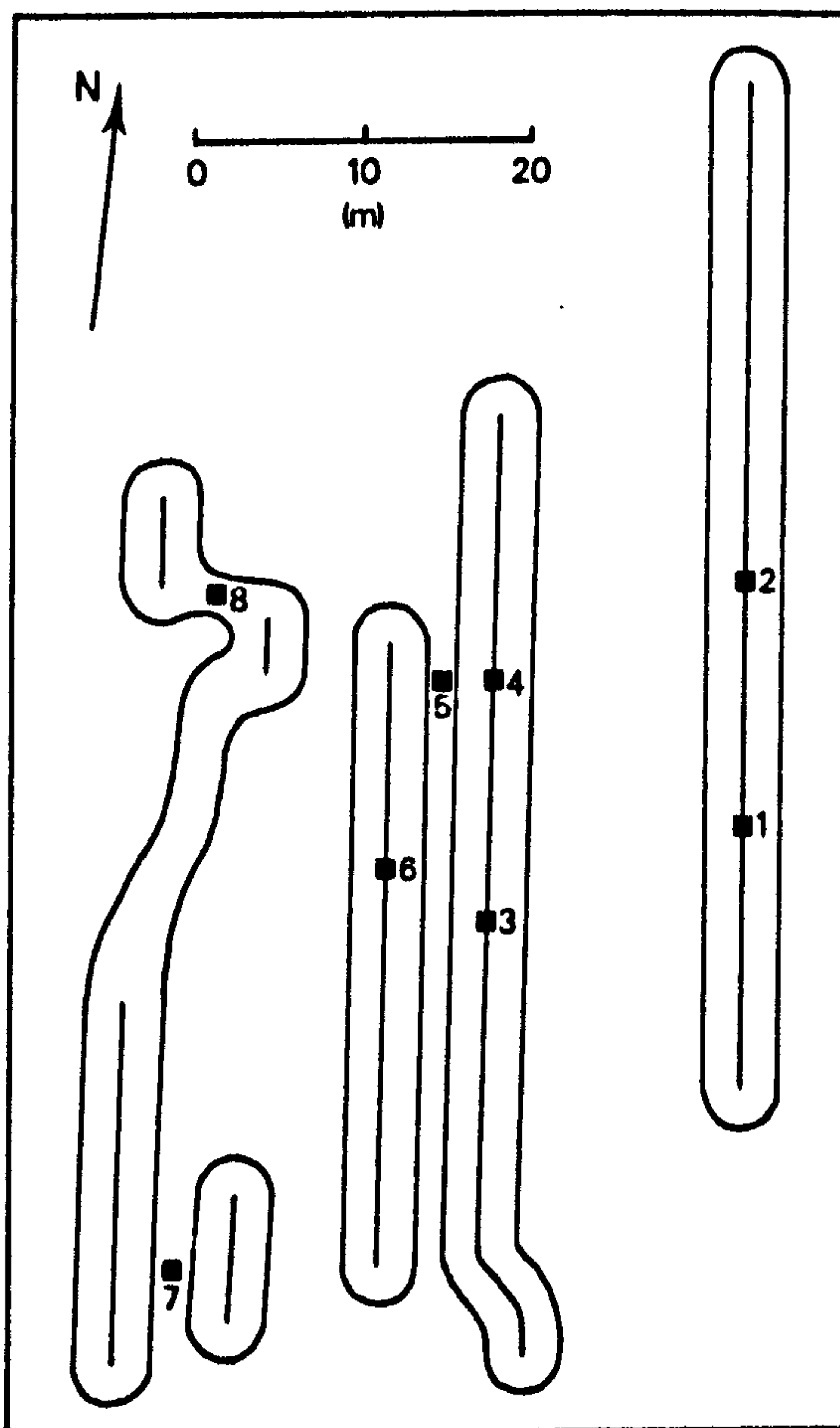
The evidence given above has shown that changes in the lithological composition of the till are not large over short (c. 1m) or long (c. 7m) vertical intervals but that sandstone does become

Fig. 7.6 Schematic map of ridges in Area D showing sample sites

more important at greater depth. Where sampling was possible (areas A and B) the till texture changes little over large vertical intervals. The generally low proportions of quartzite even among surface boulders shows that material derived from the valley sides is unimportant in the till. The clasts in many samples exhibit preferred orientations parallel to the ridge-crests, which strongly supports the idea that ice flowed in this direction, militates against the suggestion that the features were formed by the filling of crevasses and suggests that they were formed beneath active ice.

7.4. Evidence from groups of features

7.4.1. Evidence from area D



Eight samples were taken from a group of low (2-4m) features, up to 60m long with straight, near-horizontal crests. The ridges occupy the surface of an apparently thick till plateau in which some small, well defined dead-ice hollows are also present. Some short sections of ridge are collinear, suggesting that they may have been one feature that has been partly destroyed by melt-out: for instance a dead-ice hollow occurs to the SW of Site 8 (Fig. 7.6).

The features were sampled because they are more comparable, morphologically, with fluted moraines than any other features in the valley. Five samples were taken from the crests of three ridges and three were taken from intervening swales (Fig. 7.6).

Table 7.4 Data from area D

Site No.	Roundness		Form		Composition			Mean Diam.
	Sand.	Quart.	Sand.	Quart.	Sand.	Quart.	Errat.	
D1	2.52	2.16	20	16	55.9	36.9	7.2	-0.93
D2	2.68	2.64	4	16	59.1	36.8	4.1	-2.11
D3	2.36	2.30	16	8	61.5	31.4	7.1	-1.49
D4	2.64	2.08	32	40	44.0	50.1	5.9	-3.66
D5	2.12	1.96	16	-	84.8	9.7	5.5	-0.76
D6	2.40	2.82	16	-	80.5	18.4	1.1	-1.90
D7	2.52	1.96	8	32	69.2	25.8	5.0	-1.30
D8	2.20	2.64	28	20	52.3	38.3	9.4	-1.58

Sand. = Sandstone, Quart. = Quartzite, Errat. = Erratics, and Diam. = diameter.

Table 7.4 gives a summary of the results from these sites. It has been noted in other groups of results that several variables have changed consistently from site to site to give an interpretable pattern. For instance the correspondence of high clast angularity, coarse particle-size distribution and low proportions of ice-sheet erratics was taken to indicate local origin of the debris in some of the samples in Chapter 5. In the above results no such patterns emerge. Neither are there strong similarities or differences when comparing sites in the same feature (D1 with D2 and D3 with D4), from ridges and swales (D1,2,3,4,6 with D5,7,8), or from neighbouring sites (D4 with D5 and D3 with D6). The samples have variable lithological compositions, but except for D6, they do share high proportions of ice-sheet erratics.

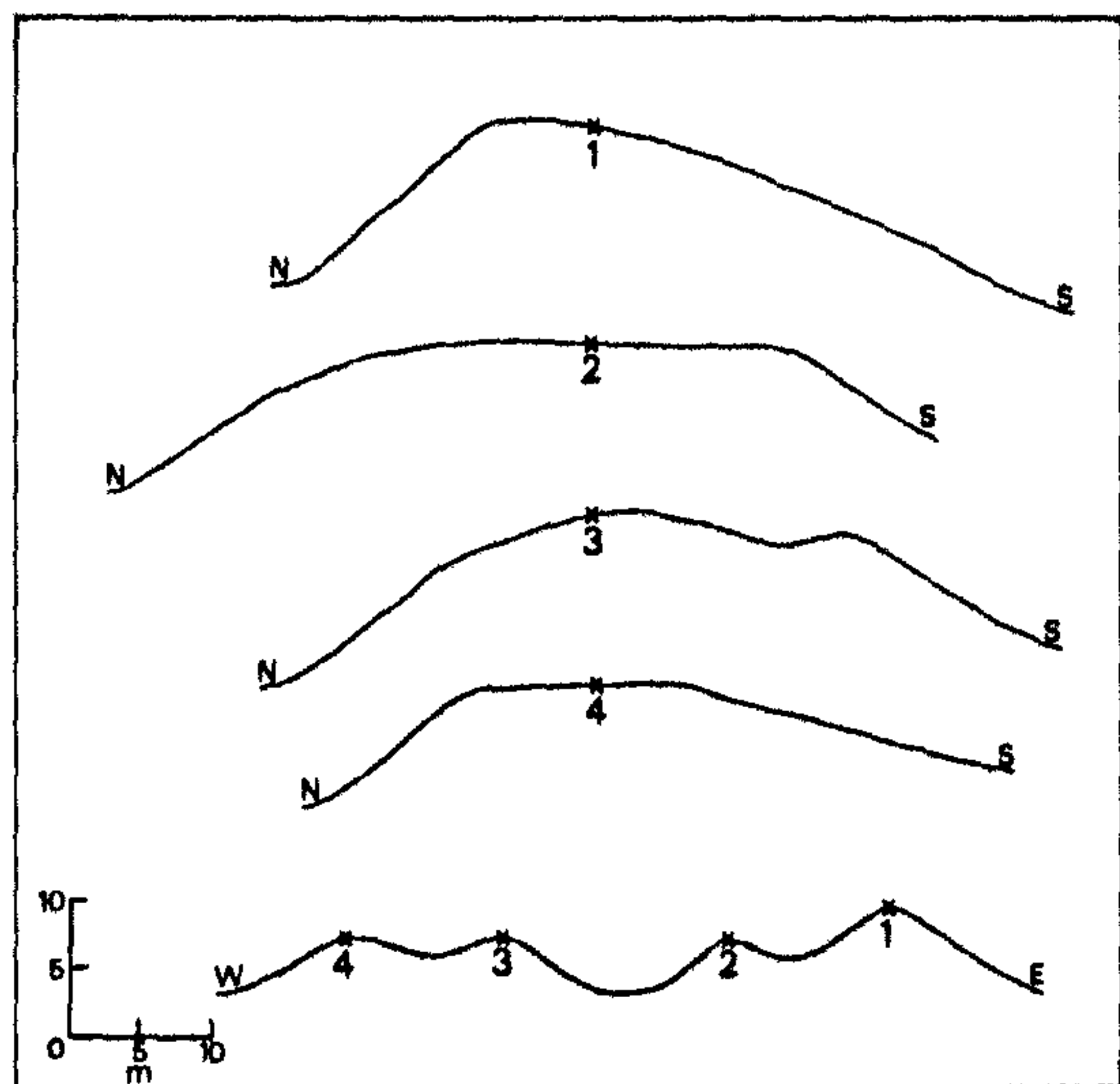
Three of the samples (D2 4 and 6) taken from ridge crests have mean diameters that are larger than almost all the samples taken from fluted moraines in the project. (The exception is site 1, Chapter 6, which, having a value of -2.27ϕ , is coarser than D2 and D6.) D4 is the coarsest sample in the whole project. It has hardly any matrix and does not display the usual secondary mode in the sand fraction. It is therefore best described as a gravel although the angularity of the quartzite clasts and the absence of sorting indicate that it does not have a fluvioglacial origin. This sample also has the highest proportion of quartzite recorded in area D. Other particle-size distributions (from D1,3,5,7 and 8) are within the range normally occupied by fluted and hummocky moraines. Therefore despite the fact that the three "coarse" samples come from ridge crests, it is not possible to infer that the ridges are generally different from the swales since samples D1 and D3 are fine and come from ridge crests.

The nine till-fabric analyses taken in these features also give equivocal results (Table 7.3). Of the four ridge-parallel orientation modes recorded two are situated in swales and two are situated in and adjacent to the crest of a ridge at one site (D1). D3 and a site on the other side of the ridge crest at D1 give no pattern and the other three analyses give oblique modes, two in ridges and one in a swale. Thus there is only limited evidence that the ridges have ridge-parallel preferred orientations in the way that would be expected in fluted moraines. On the other hand the existence of a ridge-parallel orientatation of clasts in the swales and at site D1 indicates ice-flow in this direction so the ridges do match fluted moraines in the respect that they are parallel to ice-

Fig. 7.7 Long and cross-profiles of features in
area E

flow.

7.4.2. Evidence from area E



Samples were taken from the crests of four large features (Fig. 7.7) 150m SE of area D (Fig. 7.2). They have distal slopes up to 12m high and their crests are straight and parallel to one another. On their stoss sides the features have narrow crests that rise gently to a

similarly narrow, steep-sided horizontal portion or a distinct summit before dropping away more steeply on their distal sides. Similar profiles are common elsewhere in this valley (cf. Plate 7.2) and in Strath Dionard. Viewed from the distal end, below the level of the summit, such a feature appears as a cone and it is suggested that this is relevant to the appearance of some of the features as seen from Glen Torridon (Plate 7.1). Although the cross-profile in Fig. 7.7 is somewhat contrived, since the sample sites do not fall on the same straight line, it serves to illustrate that in these features the crests are closely spaced and the swales are consequently shallow.

Table 7.5 Data from area E

Site No.	Roundness		Form		Composition			Mean Diam.
	Sand.	Quart.	Sand.	Quart.	Sand.	Quart.	Errat.	
E1	2.84	2.48	20	16	60.8	37.6	1.6	-2.19
E2	2.36	2.20	24	4	75.0	24.2	0.8	-1.85
E3	2.32	2.22	32	32	80.0	19.2	0.8	-2.07
E4	2.40	2.36	40	4	68.2	30.7	1.1	-1.25

The results given in Table 7.5 are more consistent than those for area D: the proportion of ice-sheet erratics is always small, the quartzite clasts are generally rounded in the context of the project as a whole, there are a relatively large proportion of elongate sandstone clasts and all the samples have a secondary mode in the sand fraction. The results indicate a relationship between till coarseness and feature height, not only are all the samples from these large features coarse, but in addition the coarsest till occurs in the largest feature (E1) and the finest sample is from the smallest feature (E4).

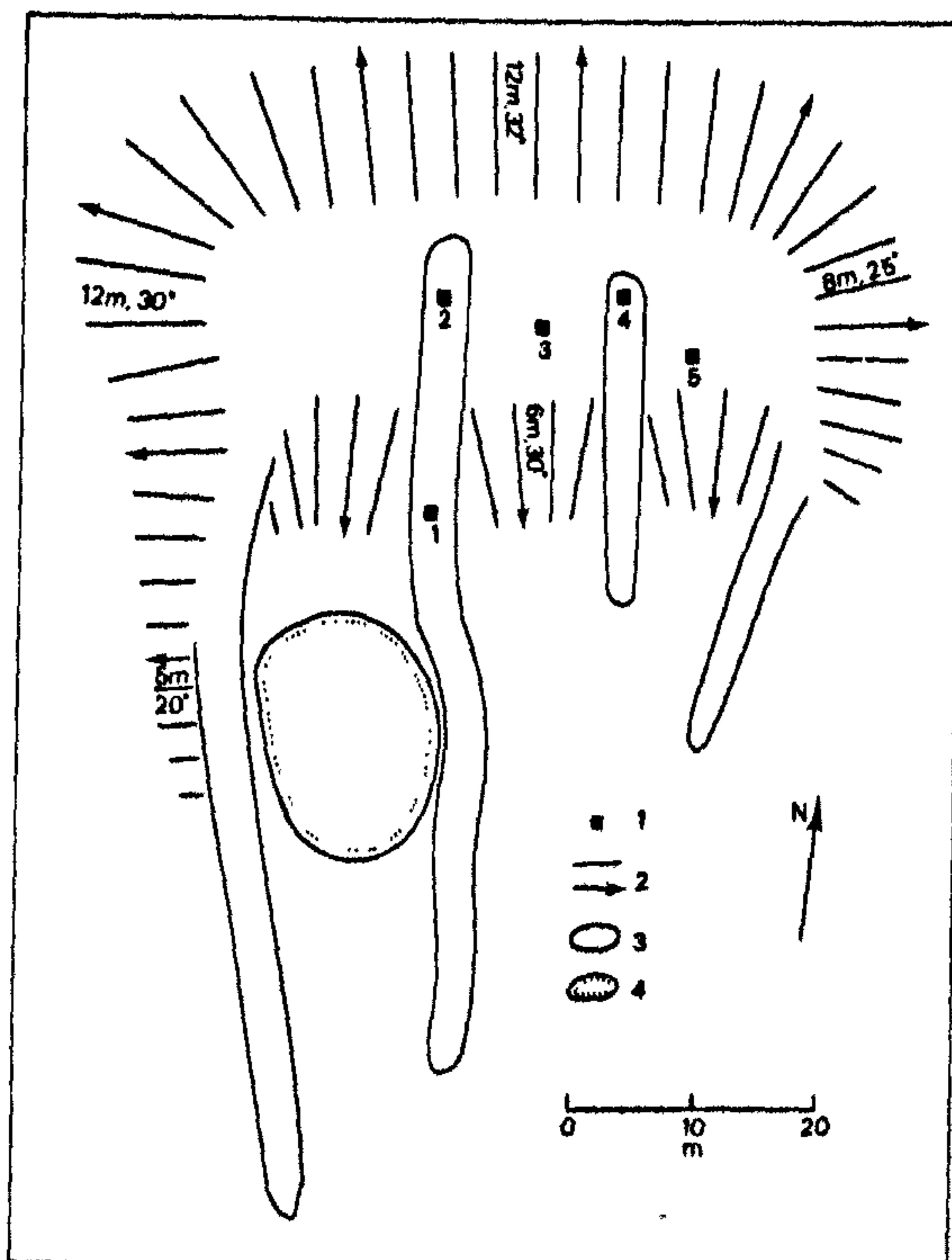
Each of the three till-fabric analyses from these features gives an interesting result: two of them have significant ridge-parallel modes while the third has two modes, one of which is parallel to the ridge and the other oblique to it (Table 7.3).

These features are the type of short, parallel ridge that invite the interpretation that they are a form of fluting. The ridge-parallel preferred orientations are positive evidence in favour of overriding by active ice flowing parallel to the ridges and other evidence contradicts alternative explanations in two ways. Firstly the dominance of sandstone in the till rules out the possibility that much of the debris fell from the valley sides onto the surface of the glacier. Secondly the consistent nature of the till and the fact that, although coarse it always has a mode in the sand fraction, together with the absence of stratification militate against final deposition from above dead-ice. The only objection to the suggestion that the features are a form of fluted moraine stems from their bulky and abrupt profiles and the closeness of their crests to one another.

Fig. 7.8 The location of sample sites in Area F

1. Sample site
2. Major slopes (arrows point down-slope)
3. Minor moraine ridges
4. Lochan

7.4.3. Evidence from area F



Some very large mounds lead away, W and then NW, from the base of the quartzite valley-side (Fig. 7.2). Since they stem from a point near the mouth of a deep gorge that cuts into this slope it seemed possible that they might represent an esker system. Fig. 7.8 shows one of these mounds about 200m W of the valley side. In this case further interest was aroused by the existence of sub-parallel ridges running S-N up the S slope of the mound onto its crest. A

circular, water-filled kettlehole occurs between the two largest of these features. Five samples were taken, three from the ridges and two from the intervening swales on the crest of the mound, to determine the nature of the ridges and the mound and the relationship between them. Sites F1 and F2 are situated on the best developed ridge which is 4m high at F1 but only 1.5m high at F2.

Table 7.6 Data from area F

Site No.	Roundness		Form		Composition			Mean Diam.
	Sand.	Quart.	Sand.	Quart.	Sand.	Quart.	Errat.	
F1	2.70	2.36	28	20	54.4	43.8	1.8	-0.96
F2	1.80	1.84	56	28	89.9	10.0	0.1	-2.68
F3	2.63	-	36	-	43.1	3.2	53.7	-2.51
F4	2.83	2.61	20	-	92.6	6.0	1.4	-2.08
F5	2.88	-	40	-	82.3	14.7	3.0	-1.47

Table 7.6 gives summarised results from the five samples. Other relevant results include four till-fabric analyses, two of which (F3 and F5) display strong S-N preferred orientations. The one at F1 has a ridge-parallel and a transverse mode and the one at F4 has two different modes oblique to the ridge-crest. In addition the results of stratigraphic sampling of the small gravel fraction show several significant trends: a decrease in sandstone towards the top of the pit at F1, and decreases in ice-sheet erratics towards the top of the pits at F3, 4 and 5, two of which (F3 and F4) correspond with an increase in the sandstone percentage (Table 7.2).

These results raise several problems. The first is an apparent contradiction between the morphological evidence and the results of sampling. Sites F1 and F2 are situated on the crest of the same ridge but the sediment at the two sites differs in almost every respect. F1 is a typical till with a well developed matrix and contains 44% quartzite and some erratics. In contrast F2 is exceptionally coarse being very poor in sand as well as in silt and clay. The ridge at this site contains many large boulders: the first attempt at digging a pit was blocked by a huge slab and the second attempt was only successful after digging round several obstructions. The sample has a large number of 'platey' sandstone clasts and both

quartzite and sandstone clasts are unusually angular. It is almost devoid of ice-sheet erratics.

The results from F1 are consistent with the idea that the ridges are fluted moraines deposited on the mound and the till-fabric analysis encourages this interpretation. However the material from F2 contrasts strongly with F1 despite its position in the same ridge and is difficult to reconcile with this explanation.

One possible resolution of the problem is to suggest that the material at F2 is derived from the underlying mound. This argument is weakened by the results from F3 (situated on the mound) which, again, contrast with F2 but the results from the other site on the mound (F5) are different from either of these two samples. Thus the mound seems to contain extremely variable material which means that the above suggestion may be valid but is difficult to test. The extreme concentration of ice-sheet erratics which occurs at F3 and may be represented at the base of the pit from which F4 was taken (Table 7.2) is made up of clasts from the fucoïd beds. This large but localised dominance of one far-travelled rock-type is difficult to explain. One may envisage one large boulder being carried to the area and broken up shortly before deposition but the clasts are not exceptionally angular. Thus some other form of transport such as a frozen raft must be invoked. Irrespective of this difficulty the evidence indicates that the debris in the mound has been disturbed very little by the Loch Lomond Advance and the evidence from F4 supports the suggestion that the surface ridges are composed of material derived from the underlying ridge.

F5 has a more conventional particle-size distribution, with more quartzite and fewer ice-sheet erratics, although the latter

increase significantly towards the base of the pit where they account for 6% of the material. F4 is in a ridge between F3 and F5 and is like them in displaying a significant increase in ice-sheet erratics (up to 12%) towards the base of the pit. Its particle-size distribution, quartzite and ice-sheet erratics proportions, and sandstone clast angularity all fall between the values recorded at these two sites. These results suggest that the material in this ridge may be derived from the underlying mound.

A further enigma is that the two sites on the mound (F3 and F5) display stronger S-N preferred orientations than those recorded in the ridges at F1 and F4.

Certain conclusions can be drawn from this puzzling area.

(i) There is no evidence that the large mound is an esker.

(ii) Despite the proximity of quartzite bedrock to the E and the evidence that much of the debris in some of the sites came from farther E, the proportion of quartzite in the till is generally low.

(iii) The orientation analyses provide evidence of ice-flow from slightly E of S to slightly W of N.

7.4.4. Evidence from area G

To the N of the mounds, of which area F is one, is a group of large, detached features all of which are elongate in a S-N direction (Fig. 7.2). Their scale and form varies but many of them have straight ridge crests and steep distal ends (Plate 7.2). Five pits were dug in the crests of four features whose distance from the

Plate 7.2 A Large hummock in profile

**Ice flowed from left to right, the feature
is 9m high and sites G4 and G5 are visible.**

valley side ranged from 200m (G1) to 400m (G4 and 5). The results are tabulated in Table 7.7.



Table 7.7 Data from area G

Site No.	Roundness		Form		Composition			Mean	
	Sand.	Quart.	Sand.	Quart.	Sand.	Quart.	Errat.	Diam.	Height
G1	2.52	-	32	4	75.9	21.2	2.9	-0.96	3
G2	2.72	2.08	20	12	62.3	30.1	7.6	-1.99	5
G3	2.68	2.48	32	24	70.5	22.7	6.8	-1.75	8
G4	2.43	2.41	36	16	77.2	19.3	3.5	-1.24	4
G5	2.24	2.35	36	40	79.6	14.8	6.6	-2.45	9

Height = Feature height (m).

Despite the fact that these samples are drawn from a large area they are more consistent than some of the other groups (e.g. F and H). Apart from Site 2 none of the pits has significant changes in rock-type proportions with depth, which reinforces the impression of consistency. This situation allows two trends to be identified. One is that there is a progressive reduction in the percentage of Quartzite in the samples from G2 through G3 to G4 and G5 which are taken from three features at increasing distance from the quartzite

source. The second is that there is a close correspondence between till coarseness and feature height. The trend, towards coarser till in higher features is broken only by the reversed positions of samples G2 and G3.

Two of the four till-fabric analyses show strong ridge-parallel modes. The others are bimodal although one of the peaks at G2 is parallel to the ridge crest. Thus the results provide evidence for ice-flow in the same direction as the ridge crests.

7.4.5. Evidence from area H

A group of short ridges, running parallel to one another in a NW direction, slopes down from the base of the quartzite hillside (Fig. 7.2). One of them can be seen to rest on the surface of the first of the series of large mounds of which the mound in area F is a member. Four samples were taken, one from each of two small ridges (H1 and H4) and two from the surface of the mound (H2 and H3), H2 being 200m W of H3. The results are summarised in Table 7.8.

Table 7.8 Data from area H

Site No.	Roundness		Form		Composition			Mean Diam.
	Sand.	Quart.	Sand.	Quart.	Sand.	Quart.	Errat.	
H1	-	1.74	-	24	2.6	97.0	0.4	-2.43
H2	-	2.16	-	24	10.1	89.9	0.0	-2.04
H3	2.12	-	24	-	88.3	3.4	8.3	-2.09
H4	-	1.82	-	28	5.4	94.1	0.5	-2.13

Samples H2 and H3 conform with the results from the top of the adjacent mound (F3 and 5) in displaying great variability. Not only

are the lithological compositions of the two samples in strong contrast but the gravel counts show that in both cases the till changes from dominance by one rock-type to dominance by the other in the space of 1m and the direction of these changes is different in each case (Table 7.2). In addition one sample is devoid of ice-sheet erratics while the other is rich in them. Both samples are coarse, a respect in which they again conform with the results from area F. Thus these results reinforce the conclusions derived from sites F3 and F5 (Section 7.4.3.).

Samples H1 and H4 are more consistent since only H1 displays a significant change in composition with depth and the range of this change is small. The two samples are similar to one another in being coarse, angular and dominated by quartzite which tends to confirm that they are representative of a consistent deposit. Each of the three samples in which quartzite is dominant has a very poorly defined secondary mode in the sand size fraction.

The occurrence of this coarse, angular, quartzite dominated debris at the base of a quartzite hillside may indicate deposition of supraglacially-derived material. However the apparent fluting of the features and the presence of some ice-sheet erratics and sandstone clasts indicate that the debris has been worked subglacially. In addition the close relationship between the quartzite and sandstone-dominated debris (evidenced by the contrast between sites H2 and H3 and particularly by the changes in composition with depth shown in Table 7.2) implies synchronicity of deposition. Thus the quartzite-rich debris may be a very locally-derived subglacial deposit, its coarseness and angularity being explained by its short distance of transport.

7.4.6. Evidence from area I

The last three sites in the valley are spaced at 50m intervals along the short end or lateral moraine on the N slopes of Sgurr Dubh. The results are summarised in Table 7.9.

Table 7.9 Data from area I

Site No.	Roundness			Form			Composition			Mean Diam.
	San.	Qua.	Err.	San.	Qua.	Err.	San.	Qua.	Err.	
I1	2.84	1.80	2.64	40	20	72	36.0	40.0	24.0	0.39
I2	1.52	1.84	2.35	72	52	84	56.3	14.4	29.3	-2.27
I3	2.12	1.70	3.04	72	76	84	60.1	15.6	24.3	-2.86

The abundance of ice-sheet erratics in these samples made it possible to measure the characteristics of the clasts. In all cases they are relatively rounded which is consistent with their long histories and distances of transport. They are also very elongate relative to the sandstone and quartzite clasts in most samples. This result can be explained as a product of the schistosity of the rocks which tends to produce plates and blades.

End-moraines are usually formed of material derived from a variety of sources and deposited by a variety of processes. It is therefore not surprising that these samples show great textural variety. I1 is the finest sample in the project, having about 8% clay and 14% silt, and I2 and I3 are the fourth and third coarsest samples in the project respectively. This contrast is reflected in the lithological composition of the samples, I1 being substantially poorer in sandstone than the other samples. The roundness of

sandstone clasts in site I1 and the concentration of fine material may suggest the action of water but the absence of sorting and stratification indicate that this agency was not important in the final depositional process.

The other two samples have very high proportions of elongates of all three lithologies, a characteristic which, along with the coarseness of the till and the angularity of quartzite and sandstone clasts, suggests the action of subaerial agencies.

A sample taken from outside the end moraine had an ice-sheet erratics content of 28.8% indicating that much of the debris in the end moraine is ice-sheet till.

7.5 Discussion

The results contradict the suggestion that the features are composed of debris derived from the valley sides and carried as a supraglacial load, the main evidence being the relative paucity of quartzite in the till, especially among surface boulders (Section 7.3.5). The suggestion that the features are composed of debris eroded from the valley floor but deposited from a supraglacial position is also contradicted by the results. The relevant evidence in this case is: the similarity between samples from the crest and the base of features (Section 7.3.1), the lack of sorted, water-deposited debris, the preservation of a lithological composition that must have been inherited from older deposits (Section 7.4.3), and the lack of a suitable mechanism for producing the observed morphology (the most likely candidate, control by crevasse pattern, having been contradicted by the results of till-fabric analysis (Section 7.3.6)).

It has been possible to conclude, on the basis of ten dominant, ridge-parallel, till-fabric modes out of twenty analyses, in and around the ridges, that the direction of ridge elongation is parallel with the former direction of ice-flow and that they were formed by active ice. However they differ from fluted moraines in some characteristics. Considered alone, the till-fabric analyses from the ridge-crests (as opposed to the swales) are inconclusive, only six out of fifteen displaying dominant, ridge-parallel modes. Some of the samples (D2 and F2) are coarser than those from any other sites in a fluted moraine; and the volume of individual features in relation to their length makes comparison with other fluted moraines and application of conventional explanations difficult.

Before pursuing this discussion further several relevant matters must be mentioned.

(i) The features that were sampled were chosen because they exhibited ridges parallel to one another. Thus they are not a representative sample of all the features in the valley. However Fig. 7.2 shows that many other features have S-N elongations. Even where features are not elongated S-N it would be rash to suggest that they were formed by greatly different processes because the likelihood of two different forms of moraine attaining their most impressive development in one area of the same valley is very small. In addition the mounds whose morphology made them most likely to be eskers have been shown to be formed of till so it is unlikely that fluvioglacial deposits are important in the area.

(ii) It has been mentioned that bedrock is often exposed in the area. This suggests that most of the till is contained in the

features but this volume is equivalent to a sheet about 2m deep covering the area. Therefore a proposed explanation of the features need not account for an unusual accumulation of debris.

(iii) The interaction of this glacier with other ice in Glen Torridon would probably have resulted in a reduction in the glacier's surface gradient leading to a deceleration of ice-flow and an increase in ice thickness at some time before the glacier reached its maximal extent.

(iv) The sample from immediately outside the end-moraine in Area I had an ice-sheet erratics content of 28.8% and the average percentage for the three samples in the end-moraine was 24.9%. It is possible that the Late-Devensian till in Glen Torridon had a higher proportion of ice-sheet erratics than that deposited in Coire a' Cheud Cnoic owing to the presence of high ground to the E of the latter area. However if it is assumed that, at the start of the Loch Lomond Advance, 25% of the till in Coire a' Cheud Cnoic was composed of ice-sheet erratics, then, estimating the present percentage of such erratics to be 5.7% (the average from the 32 samples taken in the valley), the proportion of the till in the valley that was there before the Loch Lomond Advance can be calculated.

Before the Loch Lomond Advance 1 unit of erratics constituted 25% of the till.

Therefore total till-volume was 4 units.

If no erratics escaped from the valley 1 unit constituted 5.7% of the till at the end of the Loch Lomond Advance.

The total till-volume at that time was therefore $4 \times 25 / 5.7 = 17.5$ units.

Thus the till present before the Loch Lomond Advance constitutes

$4/17.5 \times 100 = 22.9\%$ of the present till.

In this context it is relevant that quartzite boulders on the surface of the till are most abundant W of the mouth of the northernmost corrie overlooking the valley. This could be the result of a glacier having flowed W into the valley from the col before the S-N flow became dominant. Alternatively it may have resulted from the Late-Devensian ice-sheet having flowed through the col. In either case the survival of the distribution indicates that very little subsequent, down-valley movement of the till took place. Limited movement of the till is also indicated by the variability, from site to site, of the material in the large mounds in areas F and H.

(v) Of the seventy-eight samples taken in the project, thirty-two came from this valley, but of the twenty-five coarsest samples nineteen were from this valley showing that, on average, the till here is coarser than in neighbouring valleys.

(vi) The following general statements on subglacial activity are pertinent to the discussion.

(a) Lodgement is encouraged by large normal pressures exerted downwards by a glacier on its base (Boulton 1975).

(b) Erosion is encouraged by large horizontal shear forces associated with fast ice movement (Boulton 1975).

(c) High water pressure directly reduces normal pressure because, being non-dimensional, it effectively buoys up the ice (Boulton, Dent and Morris 1974).

(d) Coarse material is less easily deformable than fine material at the base of ice because the movement of one clast over another involves a large increase in the height of the space occupied

by the material. (Smalley and Unwin 1968).

(e) Low water pressure makes debris less deformable by facilitating high normal pressure.

(f) Coarse material with a sandy matrix is permeable and therefore water can move freely down the pressure gradient to relieve high pressure and strengthen the sediment (Clayton and Moran 1974).

(g) A large load in the basal layers of a glacier, increases its shear strength and reduces its plasticity.

(h) A rough bed retards the basal layers of a glacier and thus reduces the horizontal shear stress at its base.

In the light of the foregoing considerations the following explanation of the features is offered. As the main ice body advanced northwards along the valley, overwhelming whatever ice was flowing across its path from the E, a great deal of debris was available. This comprised till deposited by the Late-Devensian ice-sheet, the products of post-ice-sheet pressure release and isostatic fracturing and the products of periglacial weathering at the start and end of the Lateglacial Interstadial. As the debris was overridden or entrained into the base of the ice it retarded the basal layers and was often formed into streamlined shapes. In this context it is relevant that the typical mound profile, described above, is analogous to a *roche moutonnée* and to those end-moraines that have a shallow proximal and a steep distal slope. Other similar features have been described by Donner and West (1955). They occur on Skye and are only 2-5m high but have steep distal sides and till-fabrics orientated parallel to elongate ridge crests. On this evidence Donner and West called them drumlins although their profile is the reverse of the classic drumlin shape. It is interesting that

they were originally interpreted as dead-ice topography by Clough and Harker (1904).

It is suggested that subsequent to the initial modelling the glacier had little erosive or transportational competence. Evidence for this suggestion includes the presence of a large volume of ice-sheet erratics and the distribution of quartzite boulders. In addition several factors favouring low competence can be invoked in this valley.

(i) The interaction of this glacier with ice from N of Glen Torridon would have resulted in a slowing and a thickening of the ice ((a) and (b) above).

(ii) Abhainn Thraili would have provided an additional release for water pressure ((c) and (e) above).

(iii) The coarseness and permeability of the material would have ensured that pressure gradients were shallow and that water could escape down both valleys ((f) above).

(iv) The coarseness of the material would have made it difficult to deform ((d) above).

(v) Once stable mounds had formed they would have constituted a rough bed ((h) above).

(vi) Entrainment of debris by the ice would have initiated a negative feedback loop by reducing the mobility of the ice, hence its velocity, and therefore its erosive competence.

There are three reasons for supposing that there is a correspondence between feature height and till coarseness: (i) this valley contains the highest features and, on average, the coarsest till sampled, (ii) the correspondence is evident within groups of

samples (Sections 7.4.2, 7.4.3 and 7.4.4), (iii) correlation of feature height against mean particle diameter for all sites in this valley yields a correlation coefficient of 0.36 which is significant at the 0.10 level. However, since there are many low features (2-3 m) it is possible that this result is unduly influenced by data from a few tall features.

This correspondence between the coarseness of the till and the height of the features is consistent with this explanation since the coarsest till would be the least deformable and could therefore form the most upstanding features.

It is concluded that the work in this valley has been successful in disproving the intuitively simplest explanation that the features resulted from the deposition of supraglacial morainic till from the surface of a down-wasting area of stagnant ice. In addition several lines of evidence point to formation early in the Loch Lomond Advance under active ice and several factors have been invoked to explain the subsequent preservation^t_^ of the features in this area.

CHAPTER 8

EVIDENCE FROM FOUR OTHER VALLEYS

8.1. Introduction

This chapter deals with results derived from four locations. The data are less comprehensive than in the three preceding chapters because the object is to answer a single question, namely: how does the lithological composition of the till in hummocky moraines respond to changes in bedrock along the path of a glacier? Each location is described in a manner similar to that used in Chapters 5, 6 and 7 but the introductory sections are brief because the areas involved are smaller and the treatment is less general.

8.2 Evidence from Coire Beinn Leithe

8.2.1 Relief and geology

This valley which has a U-shaped cross-profile, drains E from between two ridges, Beinn Liath Mhor (925m), and that running from Sgurr nan Lochan Uaine (875m) to Beinn Liath Bheag (735m) (Fig. 8.1). Its head is delimited by a rocky ridge (665m at its lowest point) W of the steep-sided rock basin occupied by Lochan Uaine. To the E of the lochan the valley has a concave long profile for 3km before dropping down more steeply into a N-S through valley.

The area lies between 2 and 5km W of the Moine Thrust Plane and is traversed by several subsidiary thrust planes which result in the outcrop of several narrow strips of quartzite trending N-S across the

Fig. 8.1 Coire Beinn Leithe

1. Lochans
2. Contours
3. Watershed
4. Striae
5. Sample sites
6. Hummocky moraines
7. Quartzite

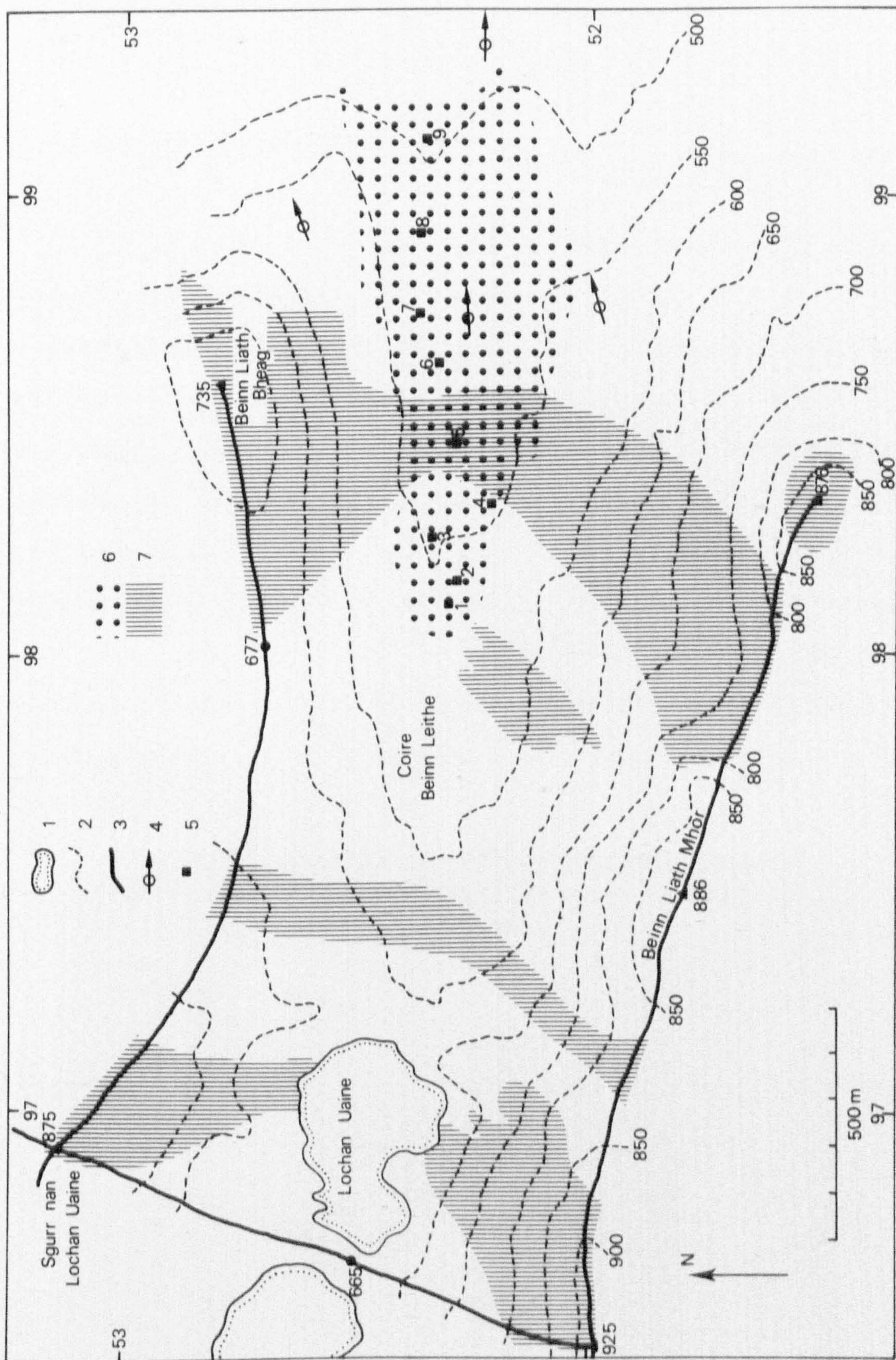


Plate 8.1 The hummocky moraines in the floor of
Coire Beinn Leithe.

Ice flowed from right to left.

valley.

8.2.2 Glacial features of the area

The upper section of the valley has some areas of drift among smooth bedrock exposures but farther E the drift is replaced by spreads of large sandstone boulders. Farther down the valley an extensive part of its floor and lower sides are covered by distinctive, subdued hummocky moraines (Fig. 8.1, Plate 8.1). The features are usually broader (across the valley) than they are long: they have shallow slightly convex W-facing slopes and steep E-facing slopes. These steep slopes are up to 3m high although the stream cuts into the till to a maximum depth of 6m indicating that the features are the surface expression of a larger volume of debris. Despite the transverse elongation of the features none of them is more than 60m wide.



8.2.3. Glacial events of the Loch Lomond Advance

Striae show that ice flowed E down the valley. At the head of the valley the glacier seems to have been in contact with ice flowing W into Coire a' Cheud Cnoic (Chapter 7). The ice-shed could therefore have migrated some distance E or W of the watershed. At its maximum extent the glacier extended 5km E of the watershed, its limit being marked by an abrupt termination of hummocky moraines. At this time ice also flowed out of the valley between Sgurr nan Lochan Uaine and Beinn Liath Bheag (Robinson 1977).

8.2.4. Presentation of the results

Nine samples were taken from pits 1m deep in the crests of features at various points along the valley. At eight of these sites particle-size analysis, rock-type composition, clast roundness and clast form measurements were taken. In addition the proportions of different rock-types in the gravel fraction were assessed at 1 m vertical intervals in stream sections at sites 3 and 7. The results show that in these two locations there is no significant difference in the lithological composition of the till at different depths, implying that the other samples are representative of more than just the surficial part of the till.

The locations of sample sites are marked on Fig. 8.1, the results are summarised in Table 8.1 and the particle-size and rock-type histograms are shown in Fig. 8.2.

Table 8.1 Data from Coire Beinn Leithe

Site	Roundness		Form		Composition			Mean Diam.
	Sand.	Quart.	Sand.	Quart.	Sand.	Quart.	Errat.	
1	2.54	2.00	16	36	59.3	39.9	0.8	-2.13
2	2.52	1.67	40	32	40.5	56.6	2.9	-1.47
3	1.90	-	8	24	92.4	7.6	0.0	-1.63
4	2.31	1.78	16	16	93.2	5.5	1.3	-0.83
5	2.56	2.12	28	36	27.5	68.6	3.9	-0.72
6	-	1.64	-	28	10.2	89.8	0.0	-0.76
7	2.54	1.68	8	16	47.2	52.7	0.1	-2.30
8	2.90	1.28	52	44	57.0	35.8	7.2	-1.07
9	-	-	-	-	62.2	27.8	10.0	-

The main pattern is that the proportions of different rock types in the till change rapidly in response to changes in bedrock. Sites 1 and 2 are situated less than 100m down valley from a small quartzite outcrop and have 39.9% and 56.6% quartzite respectively. It is likely that the glacier would have flowed over the area in a NE direction both because Beinn Liath Mhor would have been an ice source and because of ice-difffluence over the col on the N side of the valley at 677m. Therefore the ice crossing Site 2 would have travelled over more of the quartzite outcrop and this may explain why this site has a higher quartzite content than Site 1. Sites 3 and 4 are situated 200-300m farther down valley and contain only 7.6% and 5.5% quartzite. Site 5 is 100m down-valley from the start of second quartzite outcrop and quartzite constitutes 68.6% of the till while at Site 6, a short distance beyond the quartzite, the proportion is 89.8%. The rest of the valley has sandstone bedrock and the proportion of quartzite drops off regularly to 52.7%, 35.5% and 27.8% in subsequent sites.

The fact that the highest percentage of quartzite was recorded on sandstone bedrock can be explained in one of two ways. Either the

true peak in the quartzite contribution may be more than 89.8% and may occur between Sites 5 and 6, or the quartzite may extend farther E than is shown on the map. The boundary is copied from the geological survey "one inch" map and the relevant section is classed as an "uncertain boundary".

Another pattern that can be identified concerns the particle-size distributions (Fig. 8.2). In view of the results from sites 1 and 2 demonstrate that the proportion of sandstone in the till is greatly reduced by the quartzite outcrop to the W. Thus at Site 4 it is likely that most of the sandstone in the sample at Site 4 has been eroded close to the site. The particle-size distribution at the site is unusual in having a mode in the -3 to -2 ϕ fraction, suggesting that this size-fraction may be a major product of erosion. Support for this idea is gained from Site 2 where there is a notable peak in the sandstone distribution in the -3 to -1 ϕ fraction. At Sites 7 and 8 the pattern may also occur but it is less clear. Site 7 has a conventional particle-size distribution but the sandstone component peaks in the -4 to -3 ϕ fraction and at Site 8 the overall distribution has a mode in the -3 to -2 ϕ fraction although the sandstone contribution is not particularly high. In addition it is relevant that Sample A2 from the base of a hummock in Coire a' Cheud Cnoic (Section 7.3.1), which is composed of sandstone that has only travelled a short distance, has a mode in the -3 to -2 ϕ fraction.

It might be expected that other data would show some similar patterns e.g. more elongate and angular clasts in places where they can only have travelled a short distance. However no such patterns can be discerned from the angularity and clast shape results.

The proportion of ice-sheet erratics in the till is generally

Fig. 8.2 Particle-size and rock-type histograms
for samples from Coire Beinn Leithe

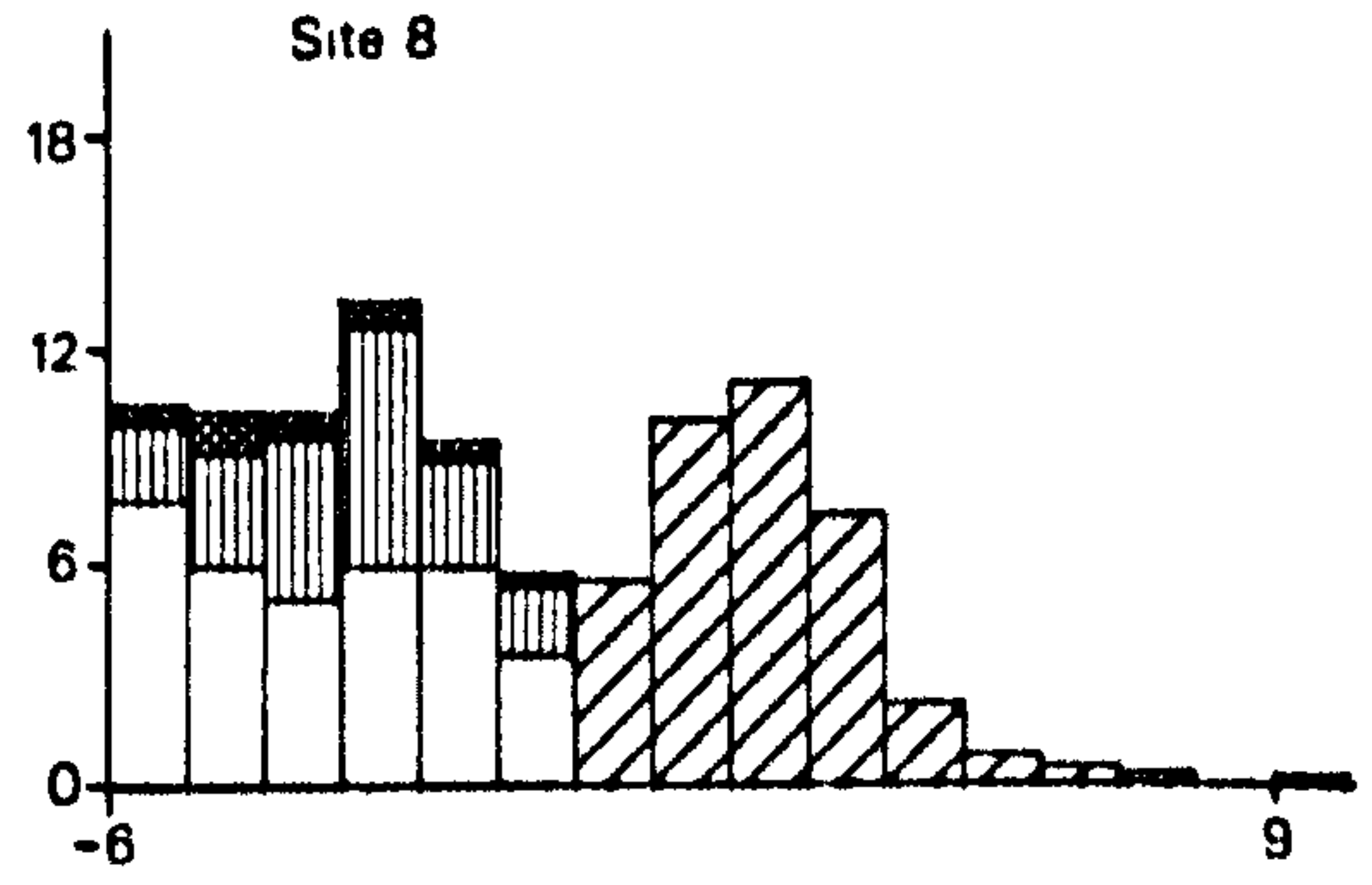
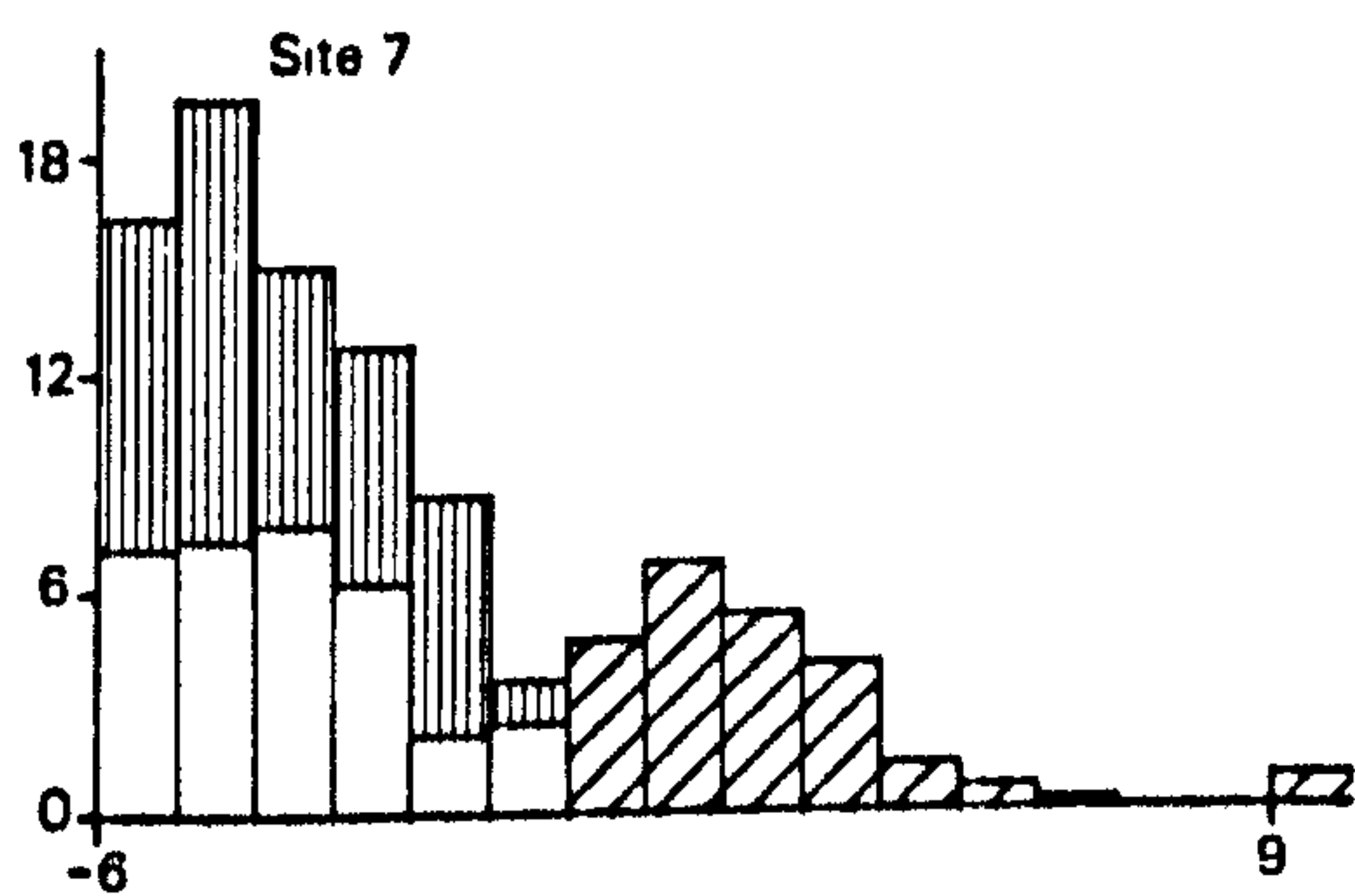
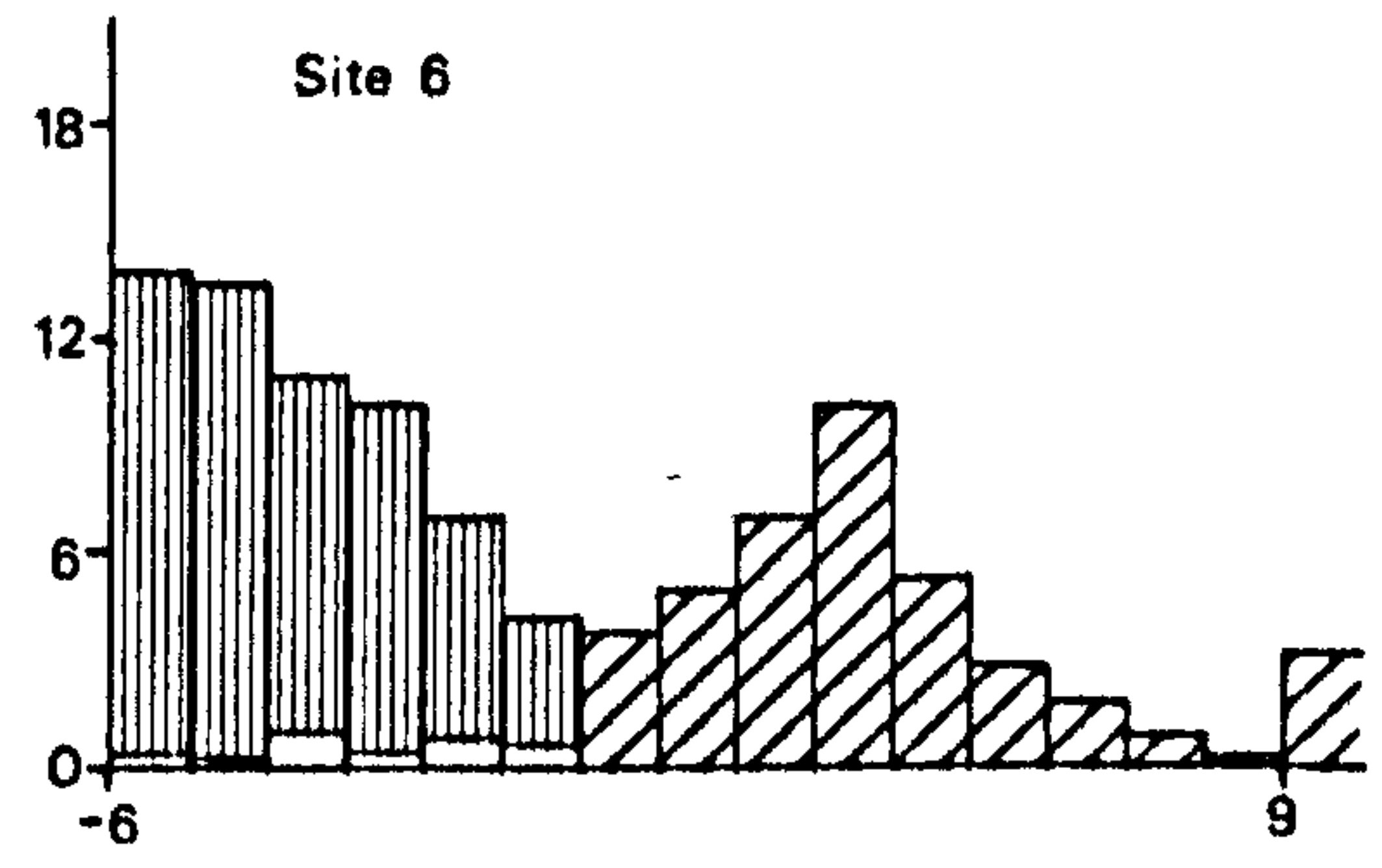
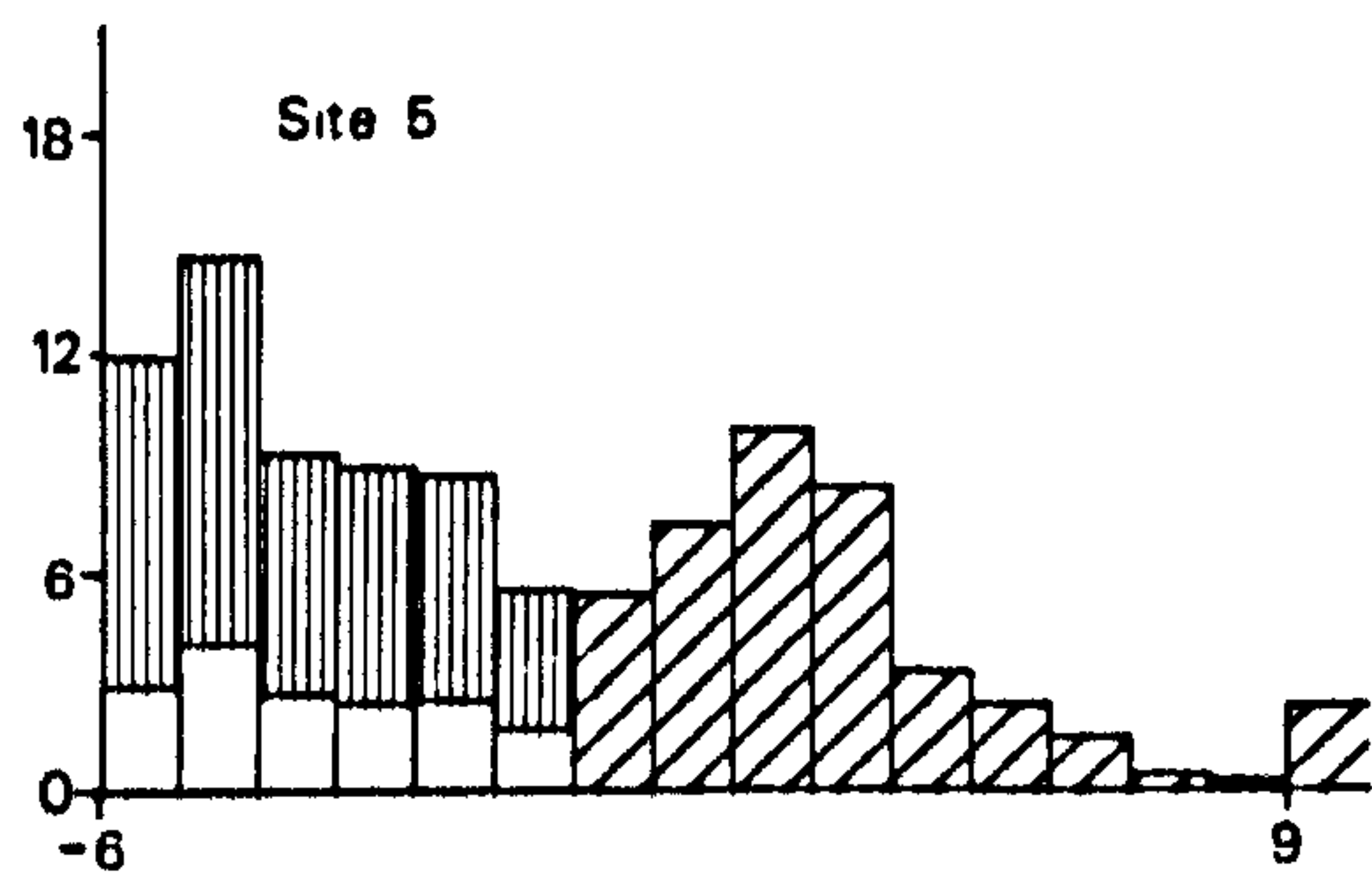
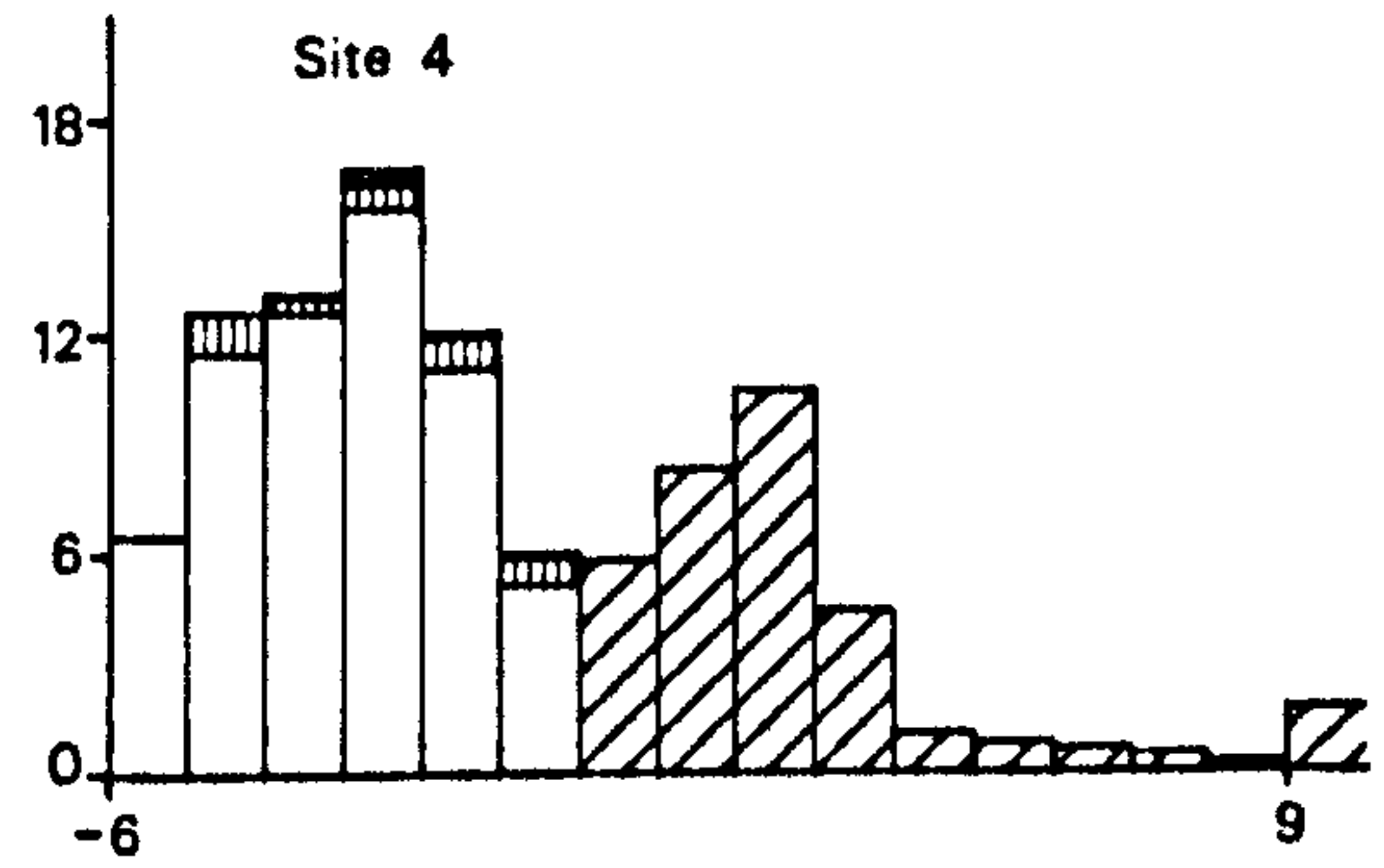
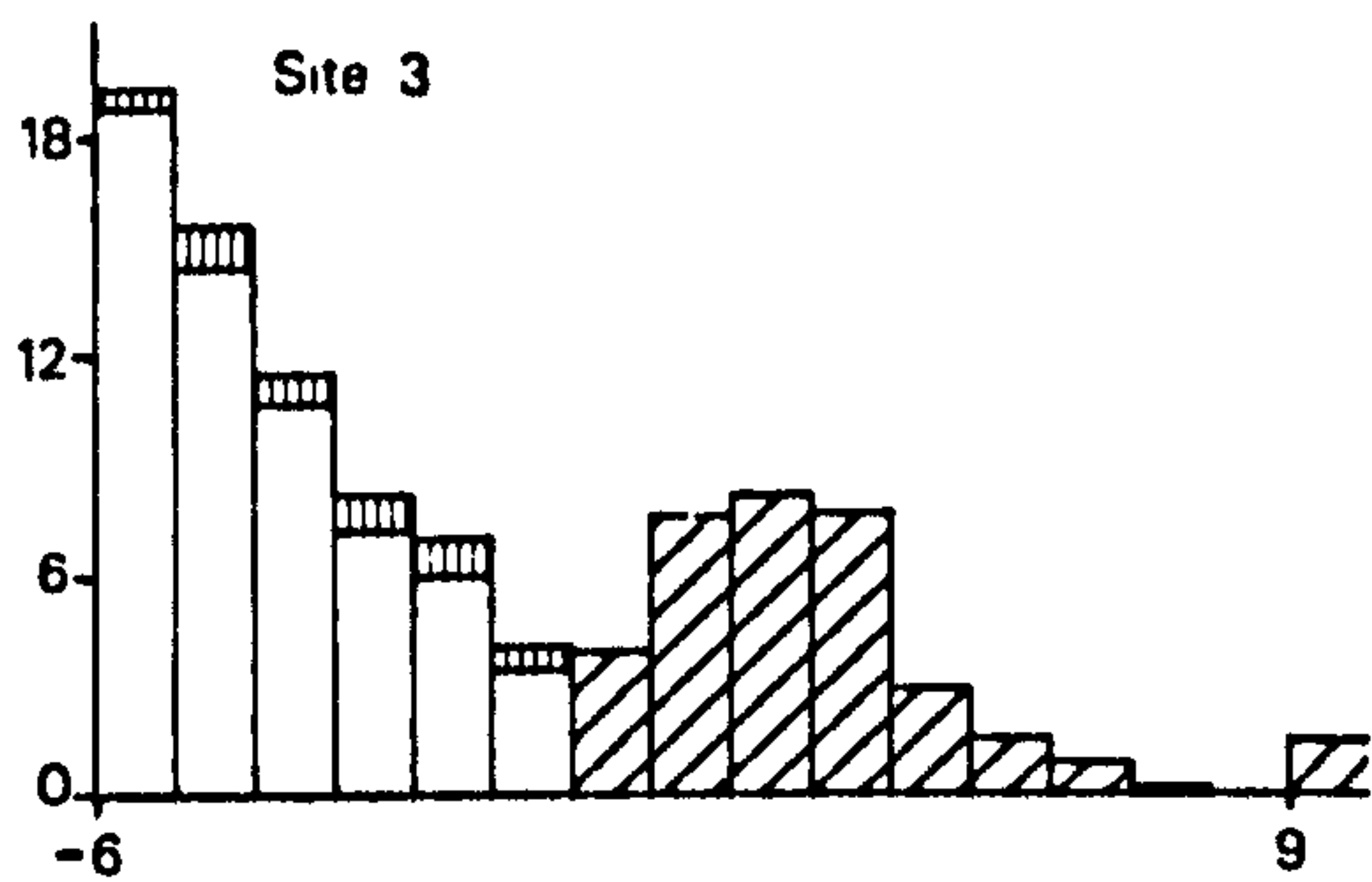
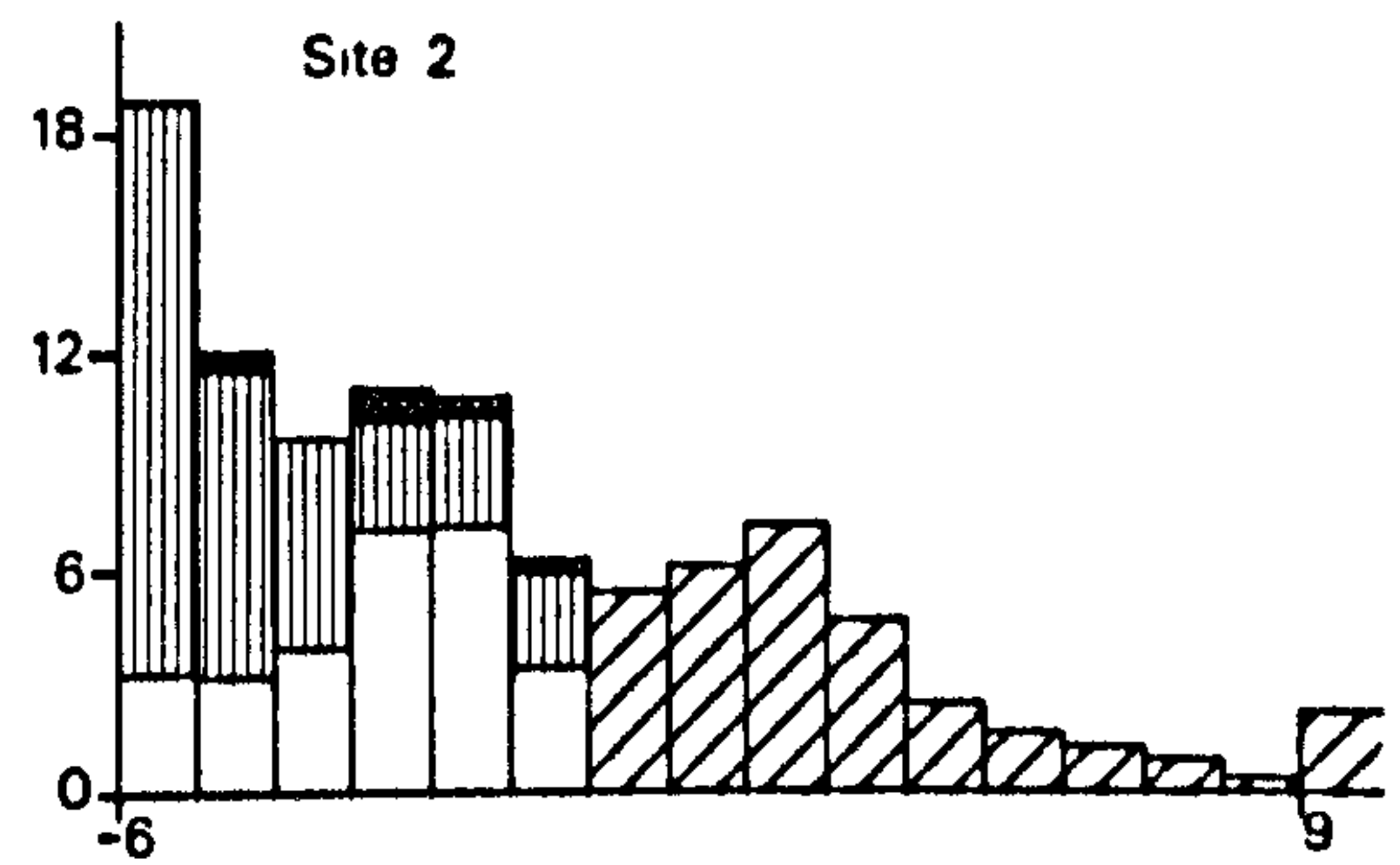
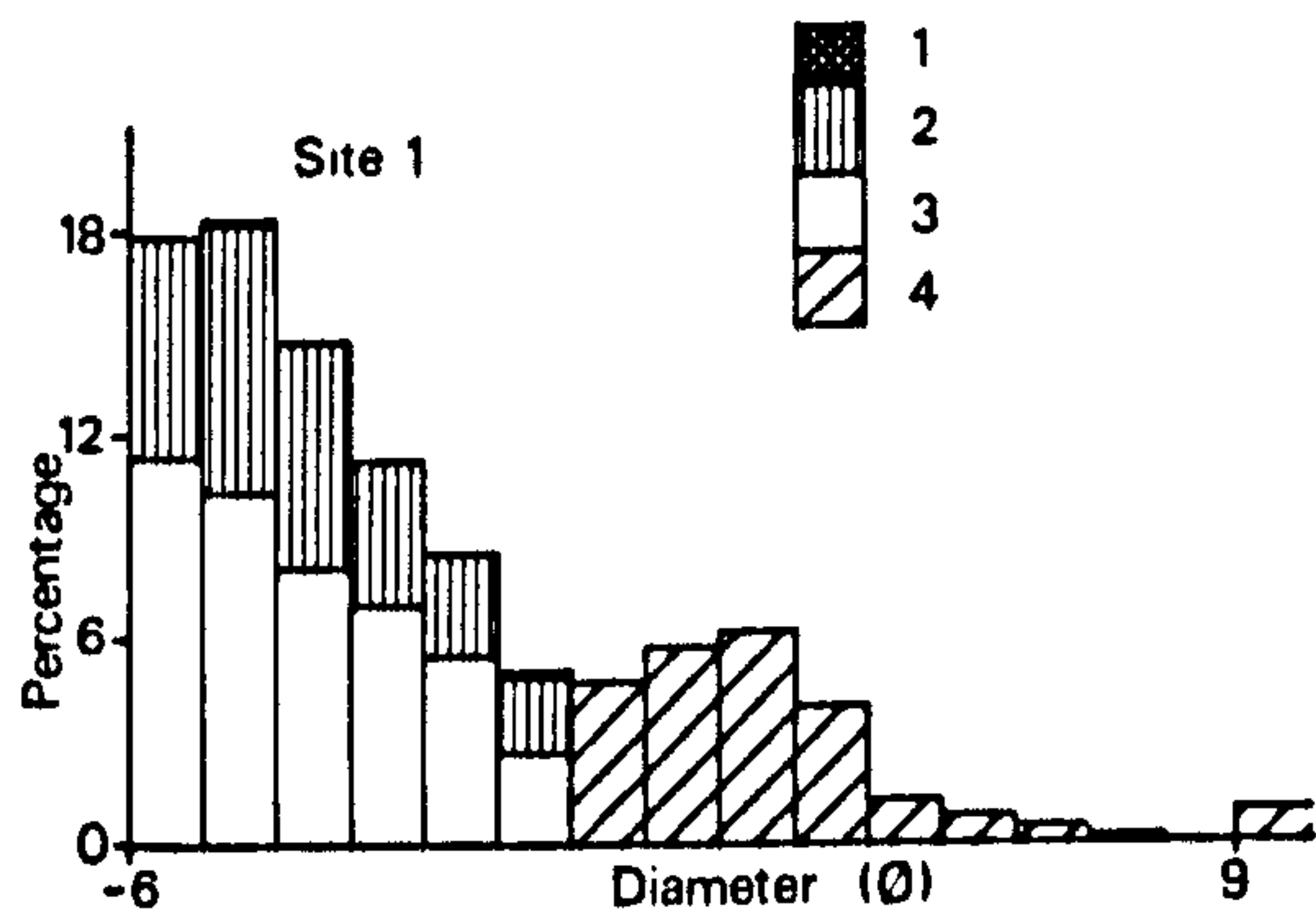
1. Ice-sheet erratics

2. Quartzite

3. Sandstone

4. Undifferentiated

Other information given for Site 1 applies
to all th graphs.



low except at Sites 8 and 9 where it rises to 7.2% and 10.0% respectively.

8.2.5 Discussion of the results

These results show that the material in the features was subglacially eroded because supraglacially derived debris could not conform so closely to the bedrock lithology. However, within the inference of subglacial erosion there is a variety of different ways in which the pattern could have been produced. These can be characterised as a spectrum between two end-members. The end-members are: (1) the situation in which almost all debris is deposited close to its place of origin, and (2) the situation in which the glacier carries almost all the debris down the valley beyond the area of the sample sites. In the latter case the features can either (a) represent the results of a long period of slow deposition of a small proportion of the eroded debris, or (b) represent the last products of the process, stranded in the valley when the ice ceased to transport material out of it. Thus the important difference is that explanation (1) ascribes the rapid changes in lithological composition to rapid deposition but in explanation (2) most of the debris is retained in transport and the changes in lithological composition result from incorporation of large volumes of the local rock-type. Assuming no losses from the system the volume of the new rock-type required to cause a given change in the composition of the till, at each bedrock contact, is calculable.

A series of sites along the valley is used as a sequence of

measurements of the state of a hypothetical volume of till moving down the valley from one site to the next. If the volume of quartzite in the till at Site 2 is taken to be 1 unit (making the total volume of the till at this point 1.77 units), and if the observed pattern is either the result of minimal deposition over a long period (2a) or represents the "last load of a stopped conveyor belt" (i.e. material that would not have been deposited here if the glacier had not become stagnant or retreated up valley) (2b), then the great reduction in the proportion of quartzite in the till between Sites 2 and 4 must be the result of the incorporation of a calculable volume of sandstone.

If 1 unit of quartzite constitutes 56.6% of the till at Site 2, and 1 unit of quartzite constitutes 5.5% of the till at Site 4, then there are $56.6 \times 1.77 / 5.5 = 17.89$ units of till at Site 4.

Similarly between Sites 4 and 6 the sandstone proportion decreases from 93.2% to 10.2%, the till at Site 4 contains 1 unit of quartzite thus:

16.89 units of sandstone constitute 93.2% of the till at Site 4, 16.89 units of sandstone constitute 10.2% of the till at Site 6, therefore there are $93.2 \times 17.89 / 10.2 = 163.46$ units of till at Site 6.

Finally, between Site 6 and Site 9 the quartzite proportion decreases from 89.8% to 27.8%, the till at Site 6 contains 16.89 units of sandstone ($163.46 - 16.89 = 146.57$) thus:

146.57 units of quartzite constitute 89.8% of the till at Site 6, 146.57 units of sandstone constitute 27.8% of the till at Site 9,

therefore there are $89.8 \times 163.46 / 27.8 = 528.00$ units of till at Site 9.

Therefore for each unit of till at Site 1 there are $528.00 / 1.77 = 298.30$ units of till at Site 9.

Since the river sections show the till to be 5m deep at Site 3 and 6m deep at Site 7 and since the features do not become notably larger and cover only a slightly wider area this prediction is clearly unrealistic.

Thus it is clear that a large proportion of the debris observed at one site must be lost to the system before the next site. Since all the above measurements were made on clasts between -6ϕ and 0ϕ diameter they do not take account of debris finer than 1mm diameter. Some of the material is lost to the system because of comminution between the two sites. For instance if much of the quartzite debris sampled at Site 2 was comminuted to a diameter finer than 1 mm before reaching Site 4 then a relatively small input of sandstone would be required to cause the observed change in the composition of the sample. However, unless these comminution products were being preferentially transported away the till would become increasingly dominated by them down the valley. In order to be preferentially transported, carried by subglacial water rather than by the ice, the debris would have to be broken down to silt and clay diameters. Since these diameters are everywhere rare in the till and since the till is not found to be finer farther down the valley it is concluded that this effect is not important over such short distances. Hence

Fig. 8.3 Coire Mhic Fhearchair

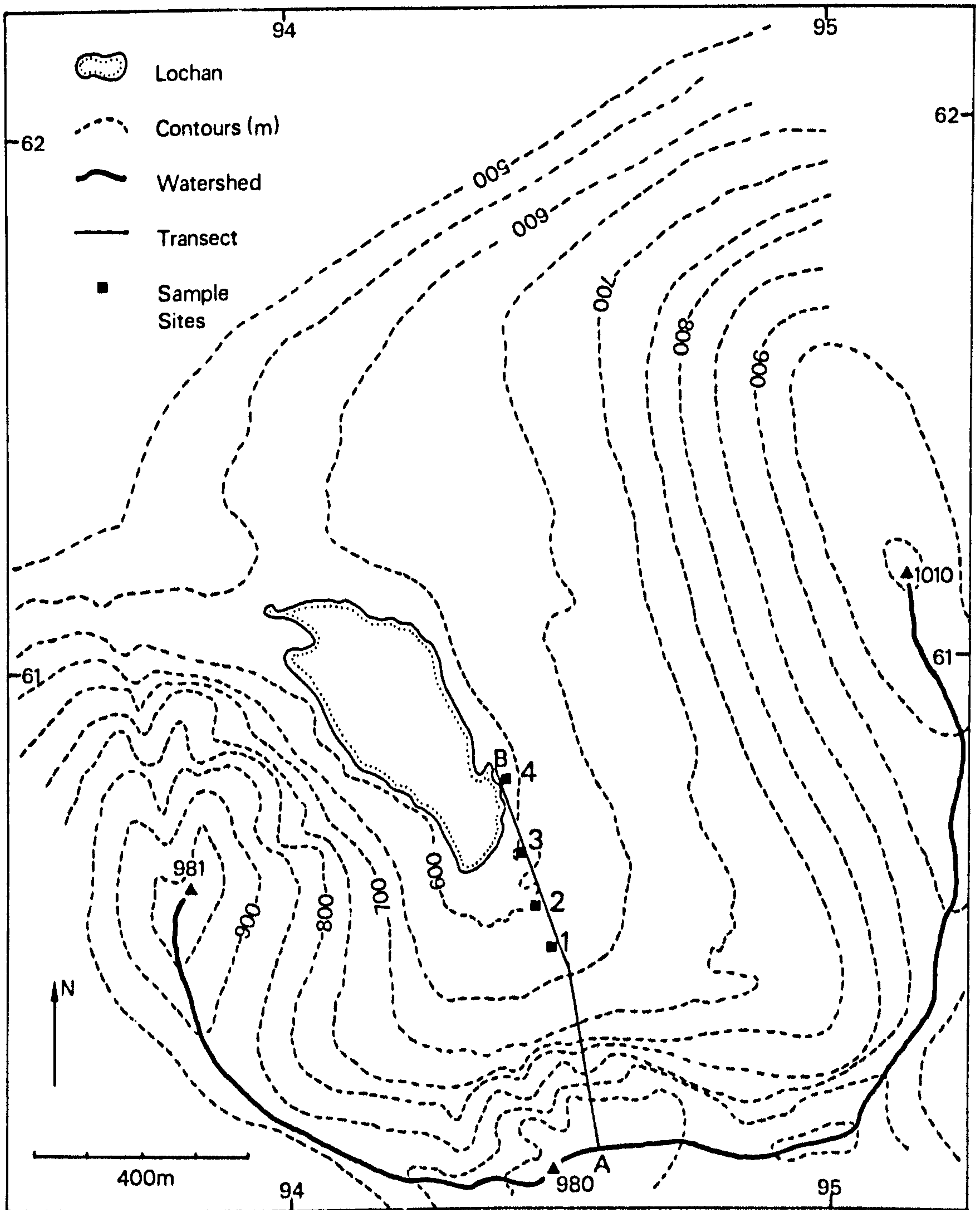


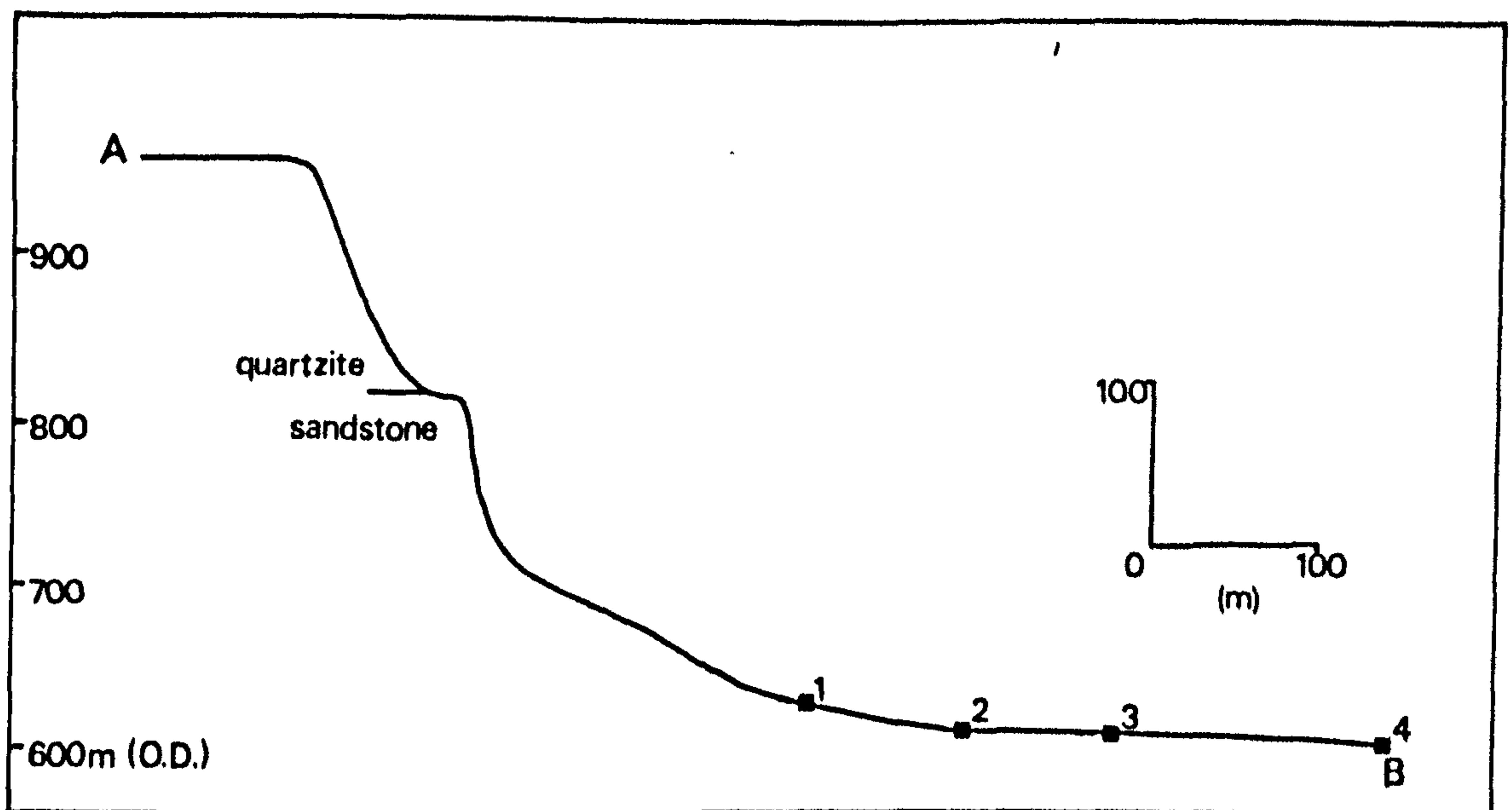
Fig. 8.4 Cross-section through Coire Mhic
Fhearchair and the sample sites

it is concluded that deposition accounts for most of the material that is lost from the system and that the explanation of the observed pattern lies close to (1) on the spectrum between (1) and (2).

8.3 Evidence from Coire Mhic Fhearchair

8.3.1 Relief and geology

Beinn Eighe has three great N-facing corries of which Coire Mhic Fhearchair (Fig. 8.3) is the westernmost. Its floor contains a deep lochan whose surface is at c. 590m. At the mouth of the corrie the ground drops sharply to 300m while steep slopes rise 400-500m above the lochan to the E, S and W. The S headwall of the corrie is an impressive cliff rising 270m from the talus at its base (Fig.84).



The unconformable junction between the sandstone and the quartzite crosses the area shown in Fig. 8.3 rising westwards. It is at 750m on the E flank of the corrie but at 950m on the W side resulting in the presence of a small cap of quartzite on the summit of Sail Mhor (981m). It crosses the S headwall at about 825m so that

the upper cliff is composed of quartzite and the lower cliff and corrie floor are cut in sandstone. It is notable that the talus at the base of the cliff is mainly composed of quartzite.

8.3.2 Glacial features of the area

Assuming that the corrie itself is almost entirely the result of glacial erosion during earlier glacial events, the main features relevant to this study are a small group of steep-sided hummocky moraines between the lochan and the talus at the foot of the headwall. The hummocks are on sloping ground so their proximal (S-facing) sides are never more than 3m high but their distal slopes are up to 6m high.

Evidence that the corrie was last occupied by locally-nourished ice is given by striae streaming out of the corrie to the NW and by a remarkable strip of quartzite boulders which runs for more than 1km across the floor in a similar direction and is discussed in Chapter 9.2.3.

8.3.3 Glacial events of the Loch Lomond Advance

The corrie is a classic ice source area and would probably have produced a simple pattern of ice-flow as the ice built up. The disappearance of ice at the end of the Loch Lomond Stadial is less easily visualised. The glacier could have retreated back into the corrie or it may have wasted-down with some residual movement.

Since the S headwall now has a large, quartzite-dominated talus

slope it is likely that a similar accumulation existed before the start of the Loch Lomond Advance and served as an initial source of debris for the glacier.

Subsequently debris would have been supplied from the exposed, frost-susceptible quartzite upper cliff and from the ice-covered, sandstone lower cliff and corrie floor. During the period when the glacier was extensive most debris eroded from the cliff would have followed a basal flow line unless it was carried out onto the glacier surface in which case it would have followed an englacial flowline. During ice wastage debris may have fallen onto the shrinking ice-mass and rolled or slid over its surface before coming to rest some distance from the cliff. Therefore the hummocks may display the results of a complex development.

8.3.4 Presentation of the results

Table 8.2 Rock-type percentages from Coire Mhic Fhearchair

Depth(cm)	Site 1		Site 2		Site 3		Site 4		
	Sand.	Quart.	Sand.	Quart.	Sand.	Quart.	Sand.	Quart.	Err.
20	68.7	31.3	72.0	28.0	83.6	16.4	66.7	33.3	
40	50.2	49.8					86.9	13.1	
60	44.7	55.3			77.6	22.4	91.7	8.3	
85	53.3	46.7					89.4	10.6	
100							85.5	13.9	0.6
120							81.0	18.0	1.0

Table 8.2 shows the results of pebble counts at small vertical intervals in four sites, the locations of the sites being given in Fig. 8.3 and Fig. 8.4. In general the results show an increasing dominance of quartzite clasts in the till at greater distances from the quartzite bedrock. Ice-sheet erratics are only encountered at

depth in Sites 3 and 4 (Table 8.3) but the sandstone and quartzite proportions show no consistent pattern of change in composition with depth.

Table 8.3 Other data from Coire Mhic Fhaerchair

Site	Roundness		Form		Composition			Mean diam.
	Sand.	Quart.	Sand.	Quart.	Sand.	Quart.	Err.	
1	1.88	1.62	68	40	54.4	45.6	0.0	-1.11
3	2.38	2.00	68	48	82.4	17.0	0.6	-2.00
4	2.00	2.30	52	24	83.9	15.6	0.5	-0.74

The results listed in Table 8.3 taken from the main till samples show other trends that occur as distance from the headwall increases. The angularity of the quartzite clasts decreases in an unbroken trend and the number of elongate quartzite clasts is least at the most distant site. Ice-sheet erratics are represented at Site 3 as well as at Site 4.

The three samples (from sites 1, 3 and 4) each have a sandy matrix and their mean diameters show that they do not differ from many of the other samples in the project. However the pits at 2 and 3 could not be dug to a greater depth because a resistant deposit of small (5 to 10cm), closely spaced, angular clasts was encountered. Many of the clasts were in contact with one another and the matrix was hard and silty causing pick-axe blows to jar the hands in a way that elsewhere would have indicated that a large boulder had been struck. The occurrence of this material was the only respect in which these features differed from the bulk of the other samples taken in the project.

Much of the rest of the corrie floor is littered with glacially transported boulders the majority of which are sandstone except in

the strip of quartzite boulders mentioned above.

8.3.5 Discussion of the results

The results allow a strong case to be made against the idea that hummocky moraines result from the deposition, from a supraglacial position, of material derived from the glacier base or from corrie headwalls and valley sides. The first of these explanations requires shear planes or debris bands in the ice to carry debris from the base to higher levels. These modes of flow have always been invoked in areas of compressive ice-flow near to the snout of a glacier (Bishop 1957, Goldthwait 1951, Weertman 1968, Boulton 1970b) or during a surge (Clapperton 1975). Since compressive flow implies a contrast between rapid flow in one part of a glacier and more sluggish flow farther down-ice it is difficult to adapt this explanation to a position 300m to 500m from a corrie headwall where ice-flow is bound to be slow and will probably be accelerating, as distance from the headwall increases, and therefore extending .

The other explanation would result in a talus-like deposit of material that had fallen from the cliff but suffered little attrition and which, judging from the composition of the present talus slope would be mainly composed of quartzite. The material in the hummocky moraines does not display these characteristics.

The reduction in quartzite content away from the headwall means that either more sandstone was incorporated into the till in this area or that much of the quartzite was deposited after only a short

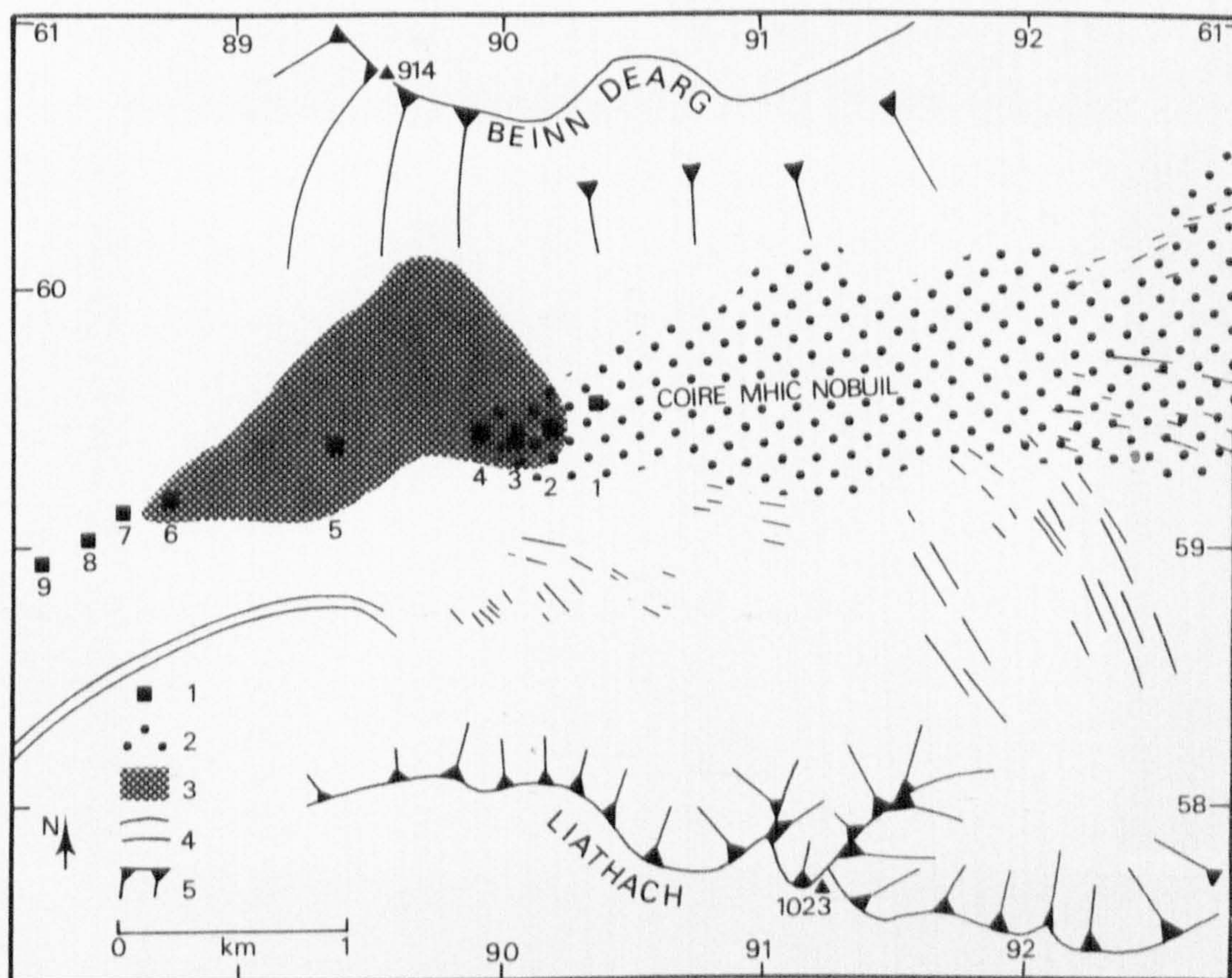
Fig. 8.5 Coire Mhic Nobuil

1. Sample points
2. Hummocky moraines
3. Lewisian Gneiss
4. Moraine ridges
5. Steep hill slopes

distance of transport (cf. Section 8.2.5). In this case the evidence is insufficient to decide which of these processes was dominant.

8.4. Evidence from Coire Mhic Nobuil

8.4.1 Relief and geology



Coire Mhic Nobuil (Fig. 8.5) is a deep, U-shaped valley between Beinn Dearg (914m) and Liathach (1,023m). It drains to the W although the deeply breached watershed at its E end rises to only 360m.

The only outcrops of quartzite in the area shown in Fig. 8.5 are two very small caps on the highest parts of the Liathach ridge. A small inlier of Lewisian Gneiss occurs on the floor of the valley.

With these exceptions the whole area shown in Fig. 8.5 is composed of sandstone.

8.4.2 Glacial features of the area

Fig. 8.5 shows that a widespread and coherent pattern of fluted moraines sweeps out of the corries on the N side of Liathach and turns westward as it descends to the valley floor. These features are evidence that a Loch Lomond Advance glacier flowed W along the valley. Further evidence is given by the a double lateral moraine on the NW flank of Liathach which begins at an altitude just less than 500m and falls westwards.

Most of the valley floor is occupied by hummocky moraines that can be subdivided into two areas with different characteristics. The features in the eastern part of the area are massive mounds (up to 8m high) with smooth, convex profiles (except where interrupted by small, steep-sided kettle holes) and a general lack of surface boulders. Some of the features are elongate and others have corrugated surfaces: since the resulting lineations are parallel to one another and conform to the coherent pattern described above they are considered to be a form of fluted moraine.

To the W the features appear chaotic, being a mixture of large and small mounds, sometimes distinct and separate and sometimes forming massive conglomerations. However they all have steep slopes and sharp crests and are littered with massive sandstone boulders. To the W of this area there is drift in the valley floor which forms mounds in some places but the topography is much more subdued.

8.4.3 Glacial events of the Loch Lomond Advance

In this area N of Glen Torridon four large mountains rise from a network of valleys whose gently-sloping floors, between 200 and 400m, are linked by low, breached watersheds. In this situation, with many ice sources and poorly defined escape routes, it is likely that the pattern of glacier build-up was complex and the eventual positions of the ice-sheds is not always clear.

In Coire Mhic Nobuil there is strong evidence that ice flowed W along the valley although, at the start of the glacial event, ice would have flowed straight down the valley side from Liathach and, perhaps, down the steep, S-facing slope of Beinn Dearg. The survival of fluted moraines oblique to the steepest line of descent from the corries of Liathach suggests that, slope-conditioned flow did not occur during deglaciation because the fluted moraines would probably have been destroyed by ice flowing across them obliquely.

8.4.4 Presentation of the results

In this valley the results consist of the proportions of sandstone and Lewisian Gneiss in the gravel fraction at nine sites across the inlier. The sites are most closely spaced a short distance down-ice of the change in bedrock in order to observe how quickly the composition of the till changes. The locations of the sites are shown in Fig. 8.5 and the percentages of the two rock-types are tabulated below (Table 8.4). No ice-sheet erratics were observed at Site 1 and at other sites all the gneiss particles were similar to

one another suggesting that ice-sheet erratics are unimportant in the till in this valley, which is more than 10km W of the Moine Thrust Plane.

Table 8.4 Rock-type proportions from Coire Mhic Nobuil

Site no.	1	2	3	4	5	6	7	8	9
Sand.	100.0	95.3	81.1	62.4	29.5	23.2	32.0	56.3	77.8
Gneiss	0.0	4.7	18.9	37.6	70.5	76.8	68.0	43.7	22.2

The results show that the composition of the till changes quickly down-ice of the start of the inlier but that a significant percentage (>20%) survives in the till to the end of the outcrop. On returning to sandstone bedrock the sandstone content rises quickly. The sequence of samples could not be continued beyond Site 9 because another glacier had flowed S to become confluent with the W-flowing ice (Sissons 1977a) thus complicating the deposits.

A related observation is that, as shown in Fig. 8.5, the hummocky moraines terminate shortly after the start of the gneiss but on the last of these features over 50% of the surface boulders (some of them up to 2m long) are composed of gneiss.

8.4.5 Discussion of the results

Despite the evidence, described in this and preceding chapters, that many hummocky moraines have subglacial origins the writer expected that these steep-sided, chaotic features between high, deep valley sides would prove to be supraglacially derived. However the

rapid inclusion of gneiss boulders and pebbles in response to a change in bedrock shows that the till was derived from the glacier base.

The paucity of till on Lewisian Gneiss is a widespread characteristic that indicates that the rock is very resistant to glacial erosion. This valley conforms to this generalisation since the volume of till is greatly reduced a short distance down-valley of the start of the gneiss bedrock (as the limit of hummocky moraines and the increased frequency of bedrock exposure in the stream bed show).

The observed rapid increase in the importance of gneiss in the till and among the boulders is made more impressive by the resistant nature of the rock-type. The reduction in the overall volume of the till shows that, in this case, the change in composition cannot be attributed to incorporation of vast volumes of gneiss; hence it must result from the early deposition of sandstone debris. This conclusion rules out the possibility of elevation of the debris to the glacier surface between its erosion and deposition because this process would require considerable down-valley movement.

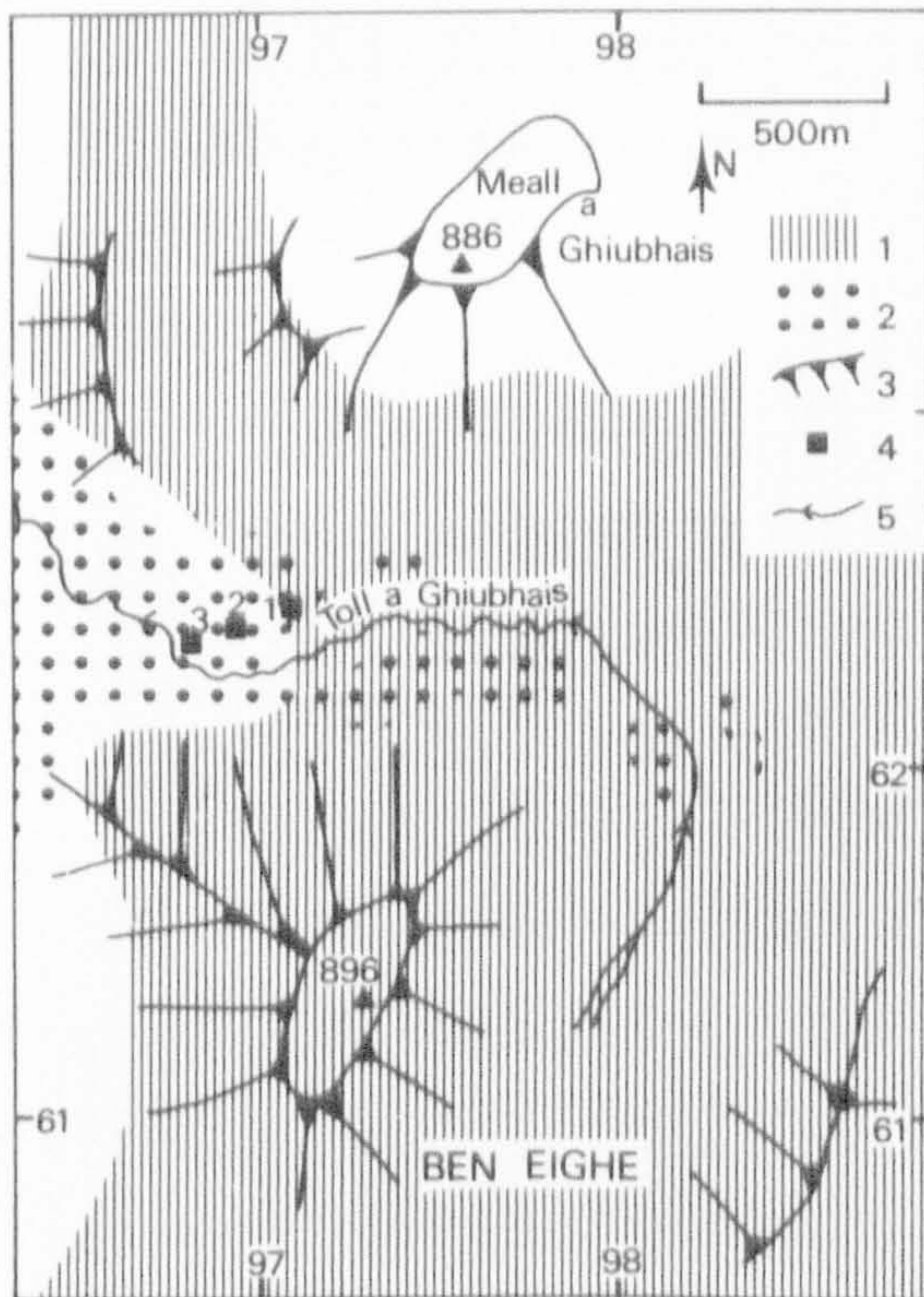
The pattern in the sites around the return to sandstone bedrock provides complementary evidence of the dependence of the till on the local bedrock, but in this case the findings are less relevant since hummocky moraines are absent.

Fig. 8.6 Toll a Ghiubhais

1. Quartzite
2. Hummocky moraines
3. Steep slopes
4. Sample points
5. Streams

8.5 Evidence from Toll a Ghiubhais

8.5.1 Relief and geology



Relatively high ground between the E end of Ben Eighe and Meall a Ghiubhais (886m) diverts the river westwards through a glacially carved valley (Fig. 8.6). The E part of the area is composed of quartzite except for an outcrop of sandstone around the summit of Meall a Ghiubhais. To the W the quartzite gives way to a larger area of sandstone and Fig. 8.6

shows that the most easterly occurrence of the junction between the two rock-types is in the floor of the valley.

8.5.2 Glacial features and events

Closely spaced hummocky moraines, up to 8m high, with steep sides, sharp crests and large numbers of sandstone boulders on their surfaces occur W of the geological boundary on the floor of Toll a Ghiubhais. To the E there are some patches of less bouldery, more subdued hummocks composed of quartzite.

The pattern of striae on the valley floor indicates that ice from the N slopes of Ben Eighe followed the same route as the present drainage and flowed from E to W along Toll a Ghiubhais.

8.5.3 Presentation of the results

Three pebble counts at sites located in Fig. 8.6 confirmed the visual impression that the till in the hummocky moraines responded sharply to the change in bedrock. Site 1 had 100% quartzite and Sites 2 and 3 (at 150m intervals down the valley) had 33.9% and 2.8% quartzite respectively.

8.5.4 Discussion of the results

In this valley it could be argued that the sandstone in the hummocky moraines was derived from the upper slopes of Meall a Ghiubhais but the existence of hummocks right across the valley floor and the very close relationship of the till to the underlying bedrock suggest that this is not the case. It is therefore considered that this is another example of large, bouldery, chaotic hummocky moraines formed from material that has been eroded from the glacier base a short distance from its present resting place. However, in this valley there is a great increase in the volume of till down-ice of the bedrock junction and the valley-floor drops more steeply in the area of sandstone bedrock. This suggests that the change in till composition is partly caused by the incorporation of large volumes of sandstone. To change the percentage of quartzite in the till from 100% to 2.8% without depositing any of that rock-type would require the volume of sandstone eroded in 300m to be 35.7 times the volume of till crossing the geological boundary. Therefore it is likely that even here deposition of much of the quartzite debris, less than 300m from the termination of quartzite bedrock, must be invoked to explain

the observed pattern.

8.6 Conclusions

The implications of each of the four pieces of work have been discussed separately. This section summarises the conclusions that have been drawn from them.

In each of these cases the results showed that the hummocky moraines are mainly composed of material derived from local bedrock. This property, in features down-ice of geological boundaries, showed that the debris (even large boulders in Section 8.4) must have been subglacially derived. In each of the sections of this chapter it was possible to show (8.2, 8.4) or suggest (8.3, 8.5) that rapid change in till composition could not be fully explained by mixing with a large volume of a second rock-type or rapid comminution of the debris but that deposition of much of the original load a short distance down-ice of its source had to be invoked. This meant that many individual particles had been transported short distances which ruled out the possibility that they had been raised to a high level in the ice before final deposition, a process which would have involved a long distance of transport and is inapplicable to a glacier source area, such as Coire Mhic Fhearchair.

CHAPTER 9

OTHER RESULTS

9.1 Introduction

The preceding four chapters have provided detailed considerations of moraines in parts of seven valleys. This chapter, as a preparation for the concluding discussion, aims to put these results in a more general context in two ways: (i) by describing observations of other types of features to indicate the variety of forms that occur and, (ii) by summarising, as one data set, the numerical results gained from all the main samples taken in the project.

9.2 Description of the features

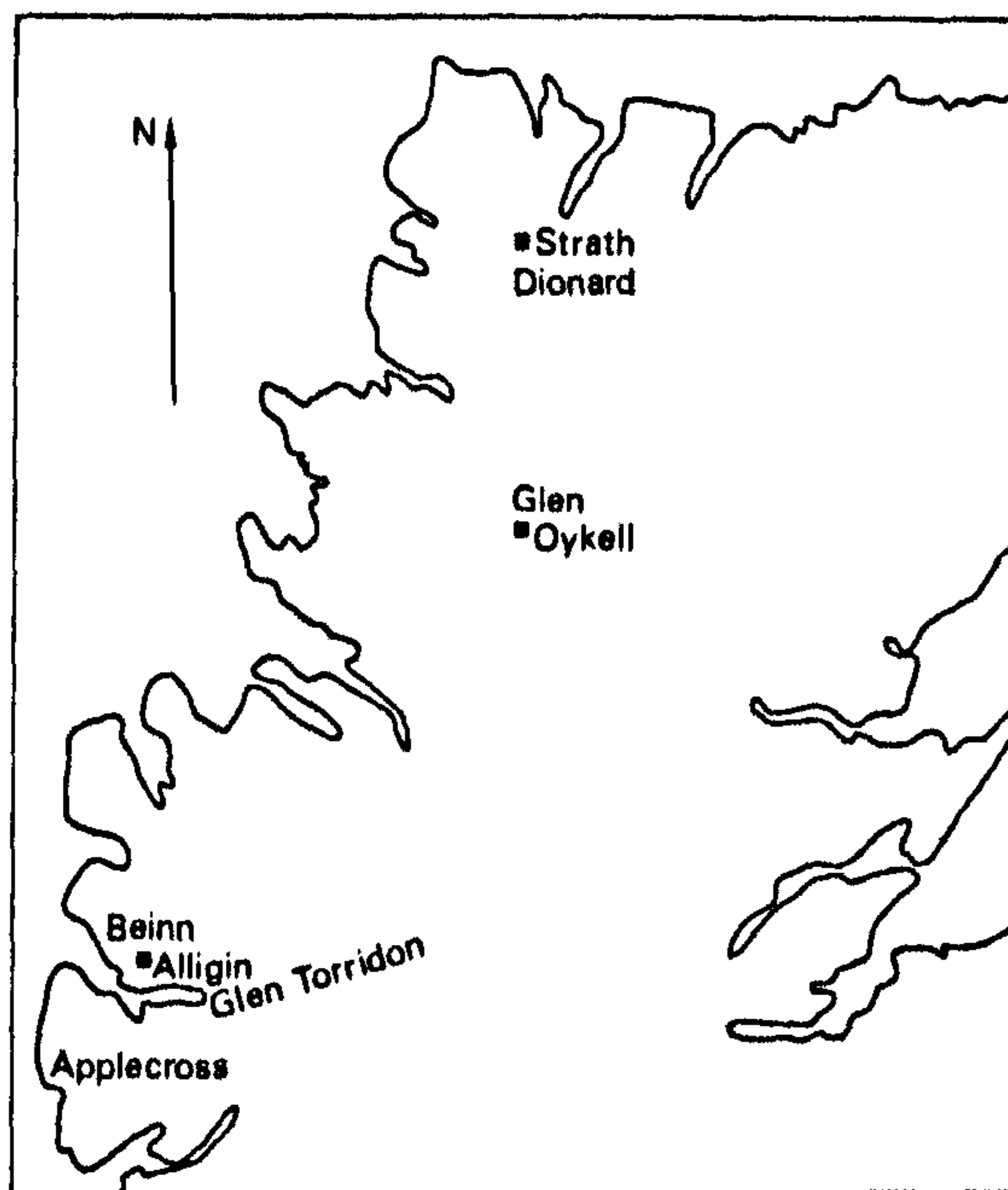
9.2.1 Large fluted moraines

In Section 6.2 a fluted moraine collinear with a medial moraine, down-ice of a mountain spur, was described. It was concluded, on the basis of rock-type composition, that the fluted moraine was mainly composed of material present before the Loch Lomond Advance. Other ridges in similar areas of confluent glacier flow have been observed by the writer.

The watershed at the head of Coire Laire (Fig 2.1) has a "W"-form profile with one col at 650m and the other at 710m. Between them is a steep sandstone knob reaching 770m. To the E of the watershed there is a group of steep-sided, closely spaced fluted

Fig. 9.1 Locations mentioned in the text

moraines up to 4m high and 100m long. Amongst these one exceptional feature runs for 600m down the valley from the slopes of the bedrock knob. It is up to 10m high towards its E end where it is composed of sandy till including some quartzite clasts. Farther W it is less high and is composed of large sandstone boulders with interstitial spaces. The junction between the two types of deposit is fairly sharp, occurring over a distance of c. 50m but the smooth ridge-crest is not affected by the change. This feature is therefore similar to that described in Section 6.2 in that it comprises a proximal part, composed of locally-derived boulders, and a distal part composed of till. However it lies in the lee of a comparatively small bedrock knob. It constitutes evidence of glacial diffluence across the col and it is likely that the knob was overridden by ice.



Another till ridge runs for c. 2km S from the easternmost spur of Beinn Alligin (Fig 9.1) (Sissons 1977) but the feature is more subdued than that described above. It also appears to have occupied a medial position between ice accumulated on Beinn Alligin and that flowing past the mountain from the N.

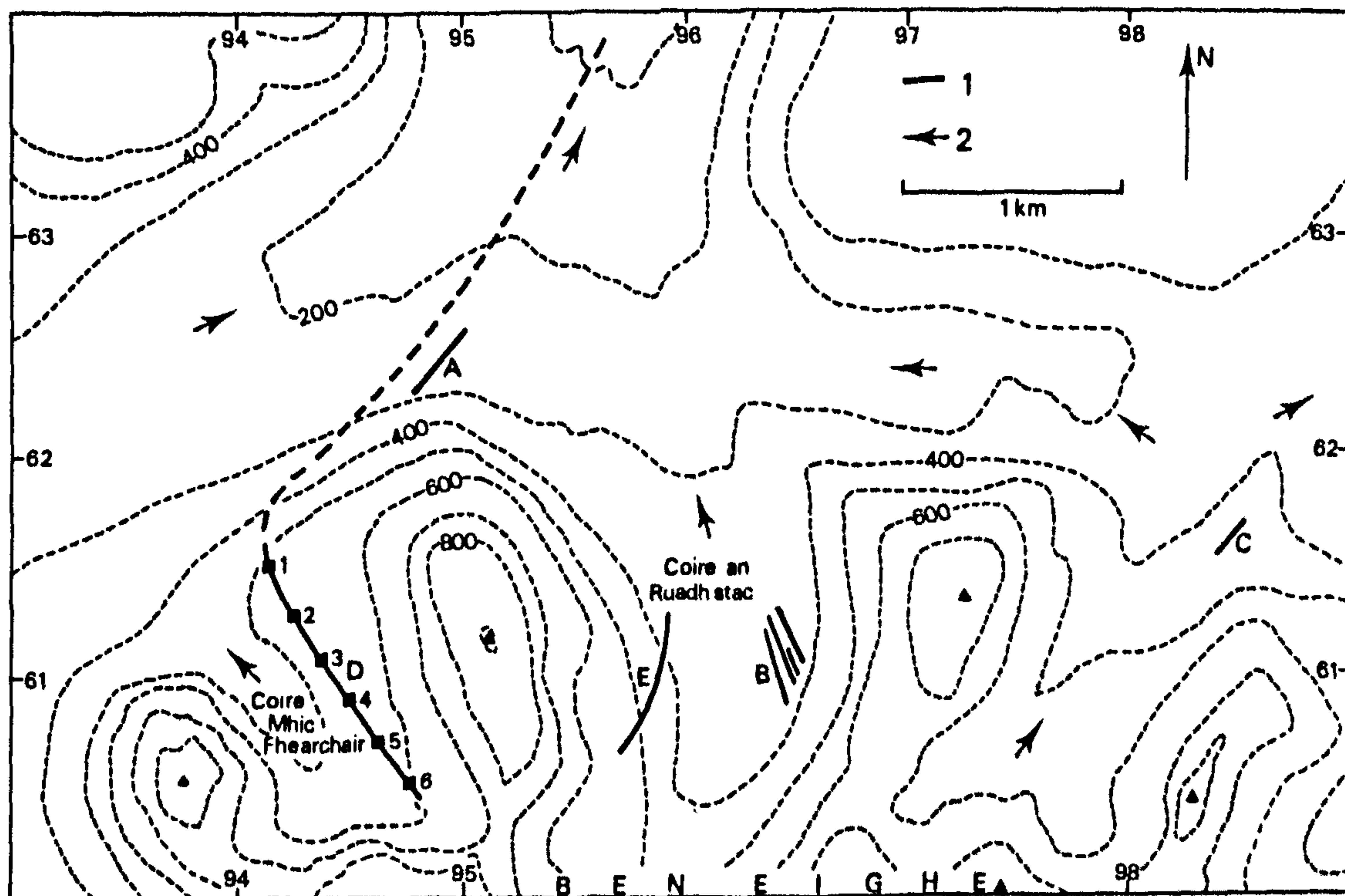
Ice flowed E from three corries adjacent on Beinn Bhan in Applecross (Fig 9.1) to form one glacier. The ice formed fluted moraines but the largest features (up to 5m high, 50m wide and 1.6km long) stem from the bases of the spurs between the corries and have therefore been described as medial

Fig. 9.2 The area N of Beinn Eighe

1. Moraine ridges and other deposits described in the text.

2. Ice-flow directions during the Loch Lomond Advance.

moraines (Sissons 1967, Robinson 1977). A further example of this type of feature occurs at the N end of a major spur of Beinn Eighe (Fig 9.2, Feature A). It is c. 300m long and tapers to the NE from a maximum height of 8m.



One other very large scale fluted moraine occurs in Coire Roill (Fig 2.1). The E side of the valley is a steep sandstone cliff with a steep-floored corrie at its S end. The valley floor has several fluted moraines but the largest starts 300m down-valley from the corrie and runs for c. 1km near to the base of the cliff. It is up to 3m high, 30m wide and its proximal end includes many large boulders, up to 3m in diameter, some of which have open spaces between them. Farther down-valley it continues to be bouldery but the clasts are set in a matrix of sandy till.

9.2.2 Other ridges

The widespread relationship between fluted and hummocky moraines has been referred to in Sections 2.4 and 3.4.2 and specific examples of associations between these two types of feature have been discussed in Chapters 5, 6 and 7. Some additional examples are described below.

In Strath Dionard (Fig. 9.1) ridges run obliquely across the valley floor. Some of them are fluted moraines but the relief of others prompted Sissons (1977a) to suggest that active ice overrode dead ice topography in which the junction between dead ice and dead ice moraine on the one hand, and active ice on the other, was a smooth surface. The area in question is a mass of drift containing five melt-out hollows. Its surface is composed of short, gently-rising ridge crests elevated 4-5m above the intervening swales. Each of the ridges, which are parallel to one another, ends in a steep distal slope and this asymmetry is reflected in the distal slope of the whole mass which is a steep slope 20m high. The ridges are therefore similar in morphology to those of Section 7.4.4 but in this case they appear to be piled on top of one another.

In Glen Oyckell a large area of steep-sided hummocky moraines has an amplitude up to 8m. Within it two parallel lines of hummocks occur and run for c. 400m in a SE direction. These hummocks are connected by ridges to form two parallel continuous features with undulating crest lines. They may have some relationship to the medial type of feature described in Section 9.2.1 since they are situated between two corries which fed the Glen Oyckell glacier during the Loch Lomond Advance (c.f. Sissons 1977a, Fig. 5).

A further example of large-scale elongate features occurs in Coire Ruadh-stac, N of Beinn Eighe (Fig. 9.2, Feature B). Here four closely spaced ridges up to 8m high with steep sides (30° to 35°) run out obliquely from the base of the steep valley side and continue for c. 300m. Some melt-out hollows occur among the ridges and the ridge crests are lowered, and sometimes displaced laterally, adjacent to them. Where they are not so modified they tend to have a stepped profile with horizontal or slightly rising sections punctuated by steep drops. Sissons (1977a) showed ice meeting the glacier in the neighbouring corrie over a col directly above the heads of these features. If some diffluence into this corrie occurred the ridges would have occupied a medial position.

9.2.3 Small fluted moraines

Subdued fluted moraines composed of till are a common feature and some examples of them have been considered in Chapters 5 and 6. Some examples of clast-dominated features are described below.

Corries on Arkle and Foinaven (near Strath Dionard, Fig. 9.1) are excavated in quartzite and their floors are littered with angular quartzite clasts up to 0.4m in diameter. When viewed on aerial photographs the corries display a strongly lineated pattern and, on the ground, subdued fluted moraines, less than 1m high and 5-10m broad, can be detected. The composition of the features is problematic since it is difficult to envisage the clastic debris being moulded by ice. However digging revealed that the clasts form only a shallow layer(c. 0.15m) over a sandy till similar to that

Plate 9.1 The train of quartzite boulders in the
floor of Coire Mhic Fhearchair
Ice flowed towards the camera.

which is common in the field area. A similar situation occurs in the easternmost corrie on Beinn Eighe (Fig. 9.2), which is also eroded in quartzite and displays a strong linear pattern when viewed on aerial photographs. Here there is one outstanding fluted moraine c. 100m long and up to 2m high with steep sided, whose surface is also composed of large angular quartzite clasts (Fig. 9.2, Feature C). A hole was dug into this feature to a depth of c. 1m but no matrix was encountered and the openwork clasts persisted. Thus either the clastic material has been ice-moulded or a former matrix has been washed out by subsequent processes. A third possibility, that the clasts represent englacial debris that was lowered onto the surface of the features, may apply to the first examples but does not explain the last-mentioned.



A different type of feature occurs on the floor of Coire Mhic Fhearchair (Fig. 9.2, Feature D, Plate 9.1). Here the upper part of the corrie headwall is composed of quartzite but the lower headwall and corrie floor are excavated in sandstone. Sandstone clasts

dominate the debris on the corrie floor but one prominent and concentrated train of angular quartzite boulders runs through the corrie parallel to the bedrock striae. At the mouth of the corrie the line is continued by more scattered boulders which run down the steep hillside towards the NE. At the foot of the slope they lie a short distance to the W of and parallel with the large ridge described in Section 9.2.1 and are visible for a farther 1.5km down-valley towards the NNE.

The feature represents the results of continuous supply of quartzite boulders to one narrow band of the glacier over the period that it took some of them to travel 3.5km, while other parts of the glacier were receiving a far smaller volume of such boulders despite the presence of imposing quartzite cliffs. Table 9.1 contains data from six sample sites at 200m intervals along the feature (located on Fig. 9.2). At each sample site the width of the band was measured and the number of quartzite clasts encountered in a 0.5m wide transect was counted. The a, b and c axes of 50 clasts were then measured so that the average clast volume and the volume of material in the feature (per unit length) could be calculated. In addition the percentage of elongate clasts ($c/a < 0.4$) was measured.

Table 9.1 Data from the boulder ridge in Coire Mhic Fhearchair

Site Number	6	5	4	3	2	1
Dist. from headwall (m)	200	400	600	800	1000	1200
Width (m)	32	34	22	14	36	53
No. of clasts	202	184	72	79	80	143
Av. clast volume (m ³)	0.09	0.11	0.14	0.10	0.17	0.23
Total volume (m ³)	18.38	19.46	10.08	8.03	13.52	33.51
Elongates (%)	24	18	32	30	24	30

Various factors must be taken into account in considering these figures. (i) Ice-flow would accelerate away from the corrie headwall thus tending to reduce the the volume found in a 0.5m wide transect at sites farther from the headwall. (ii) The boulders farthest from the headwall have been subjected to the longest period of transport and their average size would have been reduced during this process.

The reduction in the total volume of the feature from Sites 6 and 5 to Sites 4 and 3 can, perhaps, be explained by the first of these factors but the other data runs contrary to both of them. The average clast volume increases in an almost unbroken trend from less than 0.1m³ to more than 0.2m³ and the total volume of material increases at Site 2 and, especially, at Site 1. These results presumably reflect a reductions in the size of clasts and the total volume of debris supplied from the headwall during the time it took the debris at Site 1 to travel 1,200m.

The deposit does not extend as far as the headwall so its source is uncertain but it does trend towards a col at which the glacier may have been contiguous with the glacier in the neighbouring

corrie at the maximal extent of the Loch Lomond Advance, although Sissons (1977a) inferred that the ice surface did not reach this altitude and there is no evidence of ice having crossed it. If the ice did meet here plucking of debris from the spur at the confluence of the two glaciers can be invoked to augment the agency of frost shattering of the exposed cliff and explain the localised nature of the source. A shorter but similarly bouldery quartzite feature curves out from the S side of a small source area on the side of Coire Ruadh-stac (Fig. 9.2, Feature E). This feature clearly occupied a medial position and supports the suggestion that Feature D was produced in a similar situation. The size of the clasts at the different sites and, to some extent, the volume of the feature reflect a decline in the efficacy of these two processes.

There is no evidence to indicate the manner of glacier transport but the angularity of the boulders and the increase in average volume away from the headwall are difficult to reconcile with subglacial comminution while the narrowness of the feature suggests that the blocks have not been lowered from a great height.

Boulton (1978) proposed that:

"On the lee of a spur in a glacier headwall... basal flowlines can be expected to transport material from the basal transport zone up into higher level transport" (p. 798).

Further ice accumulation down-ice of the spur would have restricted the debris to a low englacial position, such an explanation explains the coarseness and angularity of the debris, the lack of evidence of comminution during transport and the narrowness of the feature.

9.3 Collective results from the main samples

Correlation analysis for eight variables (the percentage of each of each of the three lithological classes, the mean roundness of quartzite and sandstone clasts, the number of elongate sandstone and quartzite clasts and the mean particle diameter of the till) was carried out on all the samples. Spearman's Rank correlation coefficient was used and the significance of the results were tested . Apart from some autocorrelation of variables (e.g. a negative relationship between the percentages of sandstone and quartzite in the till) the correlation coefficients were small, only one of them being significant at the 0.01 level. This was a positive relationship between sandstone clast angularity and the percentage of sandstone clasts in the till ($r_s = 0.35$), which presumably reflects the influence of sites where many sandstone clasts have been deposited close to their sources. The general lack of significant relationships probably reflects the range of areas and features sampled since, as shown in previous chapters, there are relationships between variables in many of the smaller groups of samples dealt with on a local scale.

A more fruitful way of looking at the data involved dividing the samples into three groups based on the morphology of the features from which they were taken. The term fluted moraine in this section is restricted to long, low ridges with smooth, ice-parallel crest lines, while taller mounds with straight, elongate, ice-parallel crest lines are termed ridges. Other mounds lacking parallel elongations are termed hummocky moraines. The first of these groups comprises the samples dealt with in Sections 5.2, 6.2, 6.3, 7.4.1 and

Site 4 from Section 5.3. The second group includes the samples from Section 5.3 (excluding Site 4), 7.3.1, 8.2 and 8.3. The third group is composed of the samples from Sections 7.4.2, 7.4.3, 7.4.4 and 7.4.5. The three samples from an end moraine (Section 7.4.6) are shown separately. The results are presented graphically in Fig. 9.3 (A-C) and the mean values and standard deviations are shown in Table 9.2 (A-C).

Table 9.2 Descriptive statistics relating to Fig 9.2.

A Clast angularity

	sandstone			quartzite		
	flut.	ridg.	hum.	flut.	ridg.	hum.
Mean	2.53	2.48	2.37	2.28	2.22	1.84
Standard dev.	0.236	0.291	0.451	0.243	0.268	0.327

B Clast form

	sandstone			quartzite		
	flut.	ridg.	hum.	flut.	ridg.	hum.
Mean	8.00	7.85	7.35	6.58	5.46	8.23
Standard dev.	3.808	2.703	4.710	2.409	2.620	2.886

C Till Coarseness

	flut.	ridg.	hum.
Mean (Ø)	-0.99	-1.95	-1.19
Standard dev.	0.875	0.468	0.783

Some patterns of differences occur between the different types

Fig. 9.3 A The mean angularities of samples of clasts

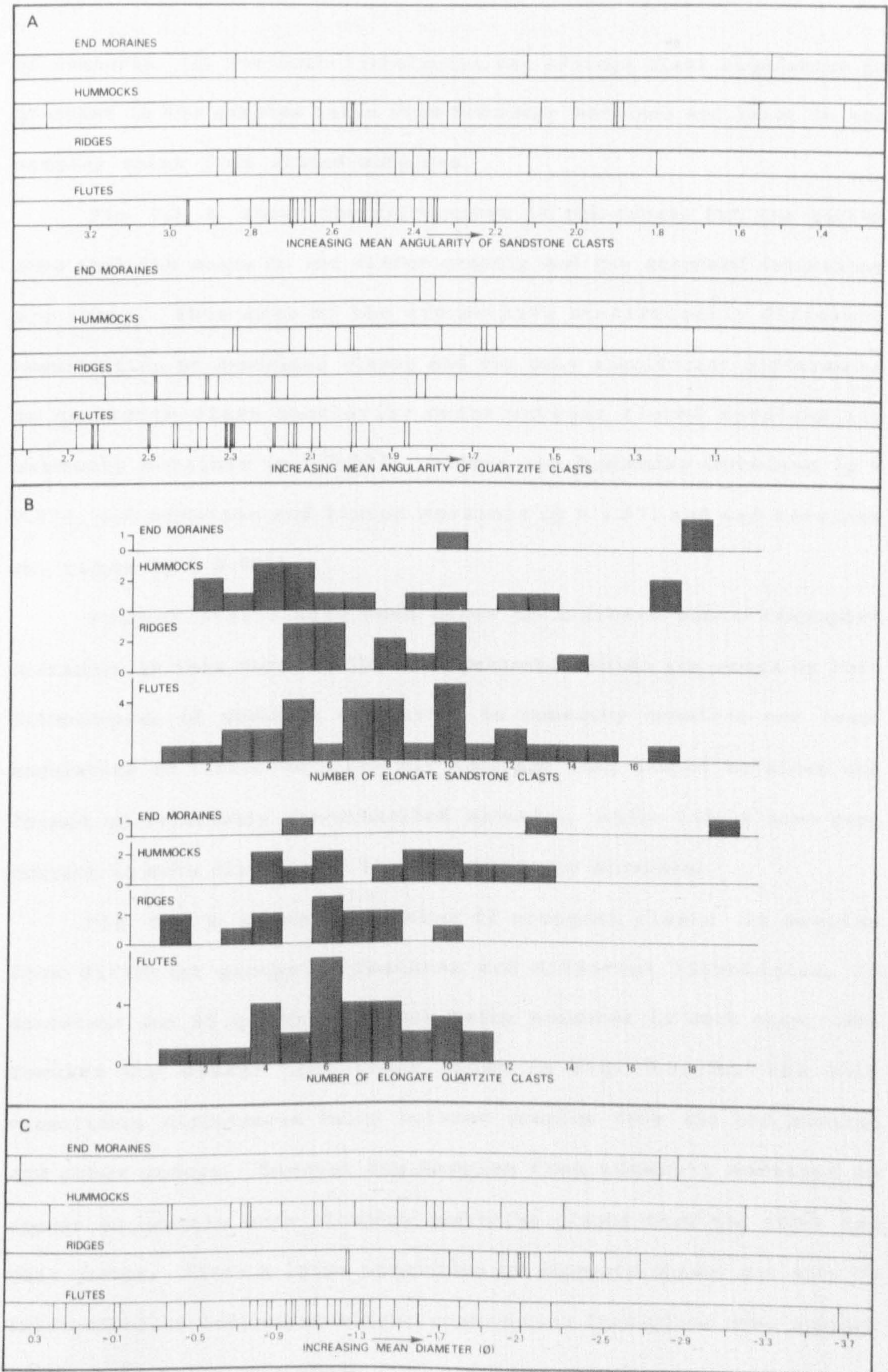
Each vertical line marks the mean angularity (roundness) of a sample of 50 clasts. The results are split into eight bands (four morphological divisions for each lithology).

Fig. 9.3 B Frequency histograms of mean clast elongation

The histogram shows the number of samples (25 in each) having different numbers of elongate clasts (c/a ratio < 0.5). The results are split into eight groups as above.

Fig. 9.3 C Mean diameters of samples

Each vertical line marks the mean diameter of a sample of till. The results are split into four morphological groups.



of features. (i) For both lithologies the average clast angularity is greatest in the samples taken from hummocky moraines and least in the samples taken from fluted moraines.

Fig. 9.3. A. shows the differences in the ranges but the tables show that the means do not differ greatly and the standard deviations are large. Thus none of the groups have statistically different angularities of sandstone clasts and the only significant differences in quartzite clast angularity occur between fluted moraines and hummocky moraines ($p = 0.001$), ridges and hummocky moraines ($p = 0.01$), end moraines and fluted moraines ($p = 0.01$) and end moraines vs. ridges ($p = 0.025$).

Angular clasts have been taken to indicate short transport distances in this thesis. Thus the patterns, which are shown by both lithologies, of greatest angularity in hummocky moraines and least angularity in fluted moraines may indicate that fluted moraines are formed of relatively far-travelled material, while ridges have been subject to more disturbance than the hummocky moraines.

Fig. 9.3. B. shows the number of elongate clasts in samples from different groups of features and different lithologies, 25 sandstone and 25 quartzite clasts being measured in each case. The results are weaker than those shown in Fig. 9.3. A., the only significant differences being between samples from the end moraine and other groups. However the samples from hummocky moraines do appear to contain more elongate quartzite clasts than the other two main groups. Since a large proportion of elongate clasts can also be interpreted as indicating slight comminution this gives some support to the suggestion made above.

Fig. 9.3. C. shows the mean diameter of particles in samples from the different types of feature. The ridges have significantly coarser till ($p = 0.001$) than either of the two other groups. This result will be referred to in Chapter 10 since it is considered that coarse till is more resistant to glacial erosion and can therefore survive in more upstanding features. The ridges are generally the tallest features sampled.

Other patterns emerge from comparisons of all the values from sandstone and quartzite samples. (i) The sandstone samples are less angular (\bar{x} (quartzite) = 2.16, \bar{x} (sandstone) = 2.46). (ii) The sandstone samples contain more elongate clasts (\bar{x} (quartzite) = 6.47, \bar{x} (sandstone) = 7.79). (iii) The standard deviations of groups of sandstone samples are usually larger than those for corresponding groups of quartzite samples, the only exception being the angularity of clasts in fluted moraines.

CHAPTER 10

CONCLUDING DISCUSSION

10.1 Introduction

This project has sought to test certain proposals and to solve certain problems relating to fluted and hummocky moraines (Sections 3.3.3 and 3.4.2). The techniques were chosen accordingly and these initial aims have been achieved (Chapters 5,6,7 and 8). In order to extend further the explanations offered a less deductive approach has been adopted in this chapter, aiming to synthesise the available information. Thus this chapter brings together and develops the matters introduced in previous chapters such as: climatic conditions and glacier responses during the Loch Lomond Stadial (Chapter 2), theories on subglacial processes (Chapter 3 and Section 7.5), the conclusions from different parts of the project (Chapters 5,6,7,8 and 9). Since this is an inductive exercise it is necessarily speculative.

10.2 Inventory of features

This section refers to features described in preceding chapters and organises them into a range of types. It illustrates that most of them are members of a continuum that differ in the degree to which they have been moulded by the passage of active ice.

Fluted moraines

There are a variety of fluted ridges that range from broad, smooth corrugations, less than 1 m high but 10-20 m wide with

parallel, continuous, even crest-lines (e.g. Section 5.2, Fig. 5.2), to higher, steeper-sided ridges which often have a more broken profile (Sections 6.2 and 6.3, Plate 6.1). The largest of these often occur in the lee of large bedrock obstructions, such as a spur or nunatak, and therefore occupy a medial position between converging ice-flows (Sections 6.2 and 9.2.1). All these forms have associations with hummocky moraines (described below). A clast dominated type of fluted moraine was described in Section 9.2.3. This type of feature was only observed on the floors of corries eroded in quartzite and was not associated with hummocky moraines. Some flute-like ridges composed of bedrock have been produced where ice flowed almost parallel to the exposed edges of gently-dipping beds of quartzite (Section 5.1.2).

Fluted moraines associated with hummocky moraines

The very subdued fluted moraines described in section 5.2 occur on the surface of a low smooth mound and a similar situation occurs on steeper hummocks N of Liathach (Section 8.4.2). A different relationship seems to apply to the fluted moraine in Section 5.3 that is not confined to the top surface of the hummock and was inferred to have been superimposed on an underlying topography. More abrupt fluted moraines occur on a large mound described in Section 7.4.1 and on a steep-sided ridge (Section 7.4.3) as well as on other features in Coire a Cheud Cnoic (Fig 7.2).

Ice-moulded hummocky moraines

The previous section described hummocky moraines on whose surface fluted moraines exist. This section deals with those hummocks whose entire form seems to have been influenced by the

passage of ice. The most striking examples of such features in the field area occur in Choir a Cheud Cnoic (Chapter 7, Fig. 7.2). These examples are elongate in the direction of ice flow. They have a variety of forms of which the simplest are steep-sided ridges with a sharp, straight crestline which rises gently from the proximal end to a distinct summit but is lost on the distal side where the slopes have a uniformly steep conical appearance (Plate 7.2). However the summit is not always near the distal end of the features; some have horizontal crests and others have more than one summit. These features constitute the group called "ridges" in Section 9.3 and can be up to 10m high. In some places large mounds with multiple, parallel ridges seem to be composed of several such features rather than being the result of surface fluting of a pre-existing mound (Section 7.4.2, Fig. 7.7) (Section 9.2.2, Strath Dionard).

Ridges composed of strings of hummocks in former medial positions have been described on Mull by Gray and Brooks (1972), who described them as fluted moraines (see Section 3.4.2). The features in Glen Oykeil and Coire an Ruadh-Stac (Fig. 9.2) may have occupied similar positions (Section 9.2.2).

Another group of features whose orderly form seems to be attributable to ice moulding are the transversely elongated mounds with a characteristic shallow proximal and steep distal slope and a surface relief of c. 2m that were described in Section 8.2.2.

Hummocky Moraines

Some hummocky moraines with no discernable order occur in Coire a Cheud Cnoic but the best examples are found N of Liathach and Ben Eighe (Sections 8.4 and 8.5). These features are typically studded with large boulders and sections indicate that similar clasts occur

within them. They are generally less distinct from their neighbours than are most of the other features described in this inventory as uninterrupted steep slopes are rare but, though complex, the topography is often abrupt. Individual features can be up to 8m high but larger conglomerations attain greater heights.

10.3 Events during the Loch Lomond Advance

In Chapter 2 the physical background of the project was set. Owing to the shortage of firm evidence the section dealing with the conditions of the Lateglacial period produced few conclusions and it was inappropriate to speculate further at such an early stage of the thesis. However it is important in this discussion to develop the subject in order to envisage the probable sequence of events and conditions in the field area.

Inferences about the sequence of climatic changes and other information, such as average annual temperatures derived from several sources, were mentioned in Section 2.5. In addition to this information is the possibility that, as the polar oceanic front migrated southwards, at the start of the stadial (Ruddiman et al. 1977), the track followed by Atlantic depressions also moved S and became more localised. Sissons (1980a) invoked this suggestion to explain the anomalously small glaciers in N Scotland as being a result of low precipitation. When the periods of advance and retreat of the polar front are considered the picture is further complicated and the findings of Duplessey et al. (in press) that the polar waters extended as far S as the Bay of Biscay raise the possibility that

the whole of N Britain could have experienced periods of high depressional activity during the southward and northward passages of the polar front and an intervening colder, drier period when the front was well to the S. Information about climatic variation within the Loch Lomond Stadial is sparse but some support for the above suggestion is given by MacPherson's evidence in Speyside (1980) (Section 2.5) while, nearer the field area Pennington (1977) detected a change during the Stadial from a very severe to a relatively mild climate.

The relative timing of such variations in precipitation and temperature and their influence on glacier mass balance is not known. The evidence of Bishop and Coope (1977) and, closer to the field area, of Robinson (1977) indicates a deterioration^{or} in the climate during the Lateglacial interstadial. Thus it is possible that gradual glacier growth could have started at an early date. Sissons (1979b) suggested that glaciers may have reformed in Scotland by 11,500 B.P. The onset of full stadial conditions after c. 11,000 B.P. was probably caused by the southward passage of the oceanic polar front, therefore corresponding with a period of enhanced depressional activity. Thus very rapid glacier advance could have occurred^r at this time, especially if high precipitation continued for some time after the climate became cooler. It is possible that the glaciers reached their limits during this period, further advance being restricted by lack of precipitation. The large size of some of the end moraines suggests that these glaciers occupied their maximal extents for a long period. Some evidence for limited retreat is given by fossil frost wedges just inside the limits of three glaciers (one mentioned in Section 2.4.2 and two on Mull (Sissons 1974 b)).

The occurrence of the Artemisia pollen stage at the bases of cores taken from the source area of two glaciers in the English Lake District (Pennington 1978) may be evidence of deglaciation of these basins before the climate ameliorated since Artemisia prefers a cold dry climate. However Sissons (1980b) considered that the glaciers retreated as a result of climatic amelioration and the pollen evidence lagged behind these events.

Despite the above suggestions of an early retreat of glaciers it is likely that most of the retreat was associated with the rapid improvement in climate at the end of the stadial (Bishop and Coope 1977) and evidence such as the apparently rapid colonisation of Rannoch Moor by thermophilous plants and trees after deglaciation (Walker and Lowe 1981) and recent evidence of a dramatic reduction in the removal of material by small streams debouching into Glen Roy while the glacier that blocked that valley was within 1km of its limit (Sissons and Cornish, in press) supports this view. Deglaciation at this time would have been rapid and the glaciers may have down-wasted, becoming stagnant except for residual down valley movement. The absence of retreat moraines and the survival of fluted moraines running oblique to hillsides below corrie mouths (Chapter 6 and Section 8.4) show that accumulation budgets were too small to sustain fresh iceflow out of the source areas at this time.

Thus it is envisaged that glaciers in the field area probably started to advance slowly before the onset of severe stadial conditions. After this event they probably advanced rapidly until lack of precipitation limited their advance and small accumulation and ablation budgets reduced their flow velocities and limited their

overall sizes. During this time they may have advanced or retreated slowly or occupied one or more still-stand positions. Rapid deglaciation and virtual glacier stagnation was caused by the return to warmer climatic conditions.

Although it is known that permafrost developed down to sea-level during the Loch Lomond Stadial it is likely that the glaciers advanced, for the most part, over unfrozen materials. During the early stages of advance the conditions would not have been severe enough to initiate permafrost, which requires a mean annual temperature of less than -1°C . At the onset of severe conditions while precipitation remained high conditions would still have been unfavourable for permafrost because snow accumulation would have shielded the ground from winter cold. During this period the supposed rapid advance of the glaciers would have limited the time available for permafrost development in their paths. The most favourable conditions for permafrost development were during the cold dry period when the glaciers would have been close to their maximal extents.

An additional argument is that the abundant fluted moraines and other ice-moulded landforms described in this thesis show that the glaciers were warm based. It is unlikely that the heat available at the glacier base (derived from friction within the ice and geothermal heat flux) w_{Δ}^u ld have been sufficient to melt permafrost during the stadial; thus it is probable that the materials were unfrozen when the glaciers advanced over them.

10.4 Synthesis

10.4.1 General Findings

The findings of this thesis, derived from a variety of glacial features in several valleys, have been remarkably consistent in showing or suggesting certain characteristics of the features and the till they contain. These generalisations are listed below with brief summaries of the evidence on which they are based.

(1) The debris was derived from valley floors.

This conclusion was based on: (i) changes in till composition in response to changes in the lithology of the bedrock of the valley floor (Sections 5.3, 8.2, 8.3, 8.4 and 8.5), (ii) lack of correspondence between till composition and the lithology of valley sides and headwalls overlooking the valleys (Sections 5.2, 5.3, 6.2, 7.4, 8.3), and (iii) the consistent presence of a considerable proportion of debris derived from the till deposited by earlier glaciations. Other evidence which suggests that the debris is not supraglacially derived is the consistent bimodal particle-size distribution and the rarity of very angular and very elongate clasts within the till.

(2) The debris has moved only short distances during the Loch Lomond Advance.

This conclusion is based on: (i) the survival of ice-sheet erratics in glacier source areas (Sections 5.2, 5.3 and 8.3) and (ii) the rapid and comprehensive changes in till composition short distances down ice of bedrock contacts. The former indicates that some debris has moved a short distance but the latter shows that the total movement during the Loch Lomond Advance has been small because

the products of any earlier long distance transport would "contaminate" the till and "blur" the observed pattern (Sections 8.2, 8.4 and 8.5).

(3) No sorting or bedding was observed in the sample pits or in natural sections and striae are extremely rare on the clasts in the till.

(4) Many of the features studied show morphological evidence of having been overridden by active ice (Section 10.2).

(5) Most of the features have well defined morphology with sharp distinct breaks of slope, constituting a fresh appearance. They are punctured by occasional dead-ice hollows that have steep sides and sometimes disrupt fluted moraines.

Other generalisations can be made about the fluted moraines in the field area. They often run oblique to hillslopes and, where abundant, they comprise coherent patterns consistent with the directions of ice-flow at the time of maximum glacier expansion. Thus it is inferred that they were formed at this time. The till in the fluted moraines is generally similar to that in the hummocky moraines but, where detailed comparisons were carried out, the fluted moraines were often found to contain a higher proportion of material that had travelled farther during the Loch Lomond Advance (Sections 5.2, 5.3 and 6.3). In Section 9.3 fluted moraines were shown to have more rounded quartzite and sandstone clasts than other features and, apparently, less elongate quartzite clasts. These results also suggest that the material in them had been carried a relatively long distance. Other features appeared to be composed of material derived from the underlying mound (Section 7.4.3).

Consideration of point (2) above yields two other inferences that are relevant. (i) If deposition continued over a long period the first deposits would shield bedrock from the glacier base, making it difficult for the observed pattern of debris correspondence to bedrock lithology to occur in samples taken from near the surface of the till. (ii) It is unlikely that erosion and deposition could take place in close proximity to one another for a long time. Both these considerations suggest that the features were formed in a short period when conditions changed rapidly to allow erosion followed by deposition of a considerable depth of till without much intervening transport.

10.4.2 Proposed Explanation

The following account of the sequence of events that may have produced these features is proposed as the simplest and most rational explanation of the above observations. It is followed by several other suggestions that have been rejected either because they fail to explain some of the observations or because they are more complicated.

In Sections 5.3.7 and 7.5 it was argued that the features were formed during glacier advance. This explanation is here extended to all hummocky moraines studied in the thesis. It is suggested that the advancing ice margin encountered large volumes of existing debris and easily erodable fractured bedrock derived from several sources: (i) till deposited by the Late-Devensian ice-sheet is shown, by the occurrence of small percentages of ice-sheet erratics, to have been present at almost all the sites. It is estimated to have accounted

for at least 22.8 % of the material now present in Coire a Cheud Cnoic (Section 7.4) and may represent a higher proportion of the material in Strath a Bhathaich (Section 6.4.3), (ii) bedrock that could have been fractured either as a result of pressure release on ice-sheet deglaciation (e.g. Battey 1960) or by rapid isostatic adjustment at that time (DeGeer 1940, Morner 1978), (iii) debris produced by periglacial weathering between the two glacial events. It may also be relevant that the area has been subjected to intense thrusting and faulting during the Caledonian Orogeny (Section 2.3) and that both the Cambrian and Torridonian sediments are well jointed and thus amenable to quarrying. Direct evidence that ice exploited planes of weakness created by faulting is provided by the occurrence of slickensides on some of the clasts (Sections 5.3 and 7.3.1).

It is suggested that this material would have been disturbed and pushed up by the advancing ice margin and would have retarded the advance of the ice. At some stage the ice would have moved over it and subsequently a number of factors (see below) would have been favourable to its relative stability in a subglacial position, allowing some features to be ice-moulded and others to ^C_Aquire fluted surfaces, but restricting the down-valley movement of the bulk of the till.

Thus thrusting by the glacier snout is seen as the main mechanism for concentration of the debris into certain areas and giving it a relief amplitude of up to 10m. It is interesting that Flint (1957) considered that moraines formed by bulldozing at the margins of expanding glaciers do not exceed 8m in height. "The small size of this feature being explained by the deduction that any more

massive heap of drift will caused the ice to fail and override the ridge" (P. 133). However pushing at the ice margin would be expected to produce transverse ridges. Some elements of such features may occur in Coire a Cheud Cnoic and the moraines described in Section 8.2 have this form but most of the features are distinct hummocks, often elongated parallel to the former direction of ice-flow.

Two main processes may have contributed to this result. Slight initial differences in the depth of the material, bedrock irregularities, or the presence of areas of resistant debris may have retarded short sections of the ice-front, creating small embayments. This would result in the till being funnelled into these areas from either side, causing further resistance to the advance of that section of the ice front. Eventually the embayment would be closed off by ice flow from the sides and over the top of the accumulated hummock which would then be passed over. Such a situation may have resulted if the glacier in S Norway producing the "saw-tooth" moraines (Matthews et al. 1979) had advanced farther and broken the ridges into distinct mounds although in that example radial crevasses were envisaged as the cause of the initial concentration of debris. Alternatively, or additionally, the ice-moulding may have taken place subglacially. Boulton (1979) considered the streamlining of bedrock hummocks (a process that may be relevant if, as argued below, the debris constituted a stable bed for the glacier). He suggested that streaming of ice around the hummock would tend to enhance the relief and that the shorter, elongate bedforms such as *roche moutonnées* would be produced in conditions of low velocity and high pressure, which are the conditions envisaged in this explanation (see below).

In Section 7.5 some important general statements about the

behaviour of subglacial materials were quoted and it was shown that many factors were favourable for debris survival in Coire a Cheud Cnoic. The statements can be summarised by saying that lodgment is favoured (and erosion inhibited) by a large pressure normal to the glacier bed, a small horizontal shear stress resulting from slow glacier flow, low water pressure, coarse debris and a rough bed. In Section 5.3.7 the emphasis was placed on a special condition, that local ice may have pushed up the features but that the ice and features were subsequently overridden by a diffluent ice-flow over a low headwall. It is suggested here that elements of these two explanations apply to many of the features studied.

The hummocks, formed early in the advance were overridden by an increasing thickness of ice which inhibited movement of particles past or over one another (a process that would involve an increase in the volume occupied by the material). The normal pressure exerted by the ice was not diminished by high subglacial water pressures because the sandy permeable till and the underlying, well-jointed bedrock enabled water to escape. Horizontal shear stresses were low because glacier flow was reduced as the climate became dry and cold. At the glacier base the hummocks constituted a rough bed further retarding the rate at which the ice could flow round them. In this situation it is likely that the plane of greatest differential movement would have occurred at or above the level of the tops of the features, especially if the ice around the hummocks had become heavily charged with debris which would make it more sluggish. Thus the longer, narrower fluted features could be created either by reworking of the surfaces of the hummocks or by deposition of material from farther up

the valley. To explain areas where large hummocks do not display ice-moulding or fluting (Sections 8.4 and 8.5) one can invoke greater coarseness of the till (indicated by the profusion of boulders in these features), and confluence with other glaciers a short distance down-valley of the features (which would have caused an additional deceleration of ice-flow).

This proposal satisfies all the generalisations made at the beginning of the section. The debris is derived from the valley floor, and is formed into hummocks in a short period during the earliest movement of the Loch Lomond Advance. Since the hummocks are formed early in the glaciation it is possible for their surfaces to be fluted when the glaciers are at their maximum extent. The rarity of striae on clasts, the sharpness of the morphology and the conspicuousness of dead-ice hollows are all consistent with the debris being bulldozed by the ice but not being entrained into it. Entrainment would probably result in long transport distances and a more subdued topography after deglaciation. The lack of sorting and bedding is also consistent with this explanation and would not be expected if the features were formed during deglaciation.

Of the factors favouring survival of the debris suggested above the only one that is measurable is the coarseness of the till. It has already been commented that a sandy matrix and a high proportion of clasts is a general characteristic of the till but closer inspection of the data suggests a more specific relationship between debris coarseness and resistance to erosion. (i) In Coire a Cheud Cnoic (Chapter 7) there is a correspondence between feature height and till coarseness that gave a statistically significant correlation coefficient for all the samples in that valley. A similar

significant relationship exists for the samples from the whole project. However, since, in both cases, there were very many low heights (2-4m) and only a few large features (8-10m) it seemed likely that the relationship was being unduly influenced by these few results and therefore the feature height variable was excluded from the correlation analysis. (ii) In four locations referred to in Chapter 7 two samples were taken from one feature: in each locality the samples from the distal end of the feature are coarser than those from the proximal end (Table 10.1).

Table 10.1 Till coarseness in pairs of samples from four features

Feature no.	Samples	Proximal	Distal
1	D1 and D2	-0.93	-2.11
2	D3 and D4	-1.49	-3.66
3	F1 and F2	-0.96	-2.68
4	G4 and G5	-1.24	-2.45

(values are mean diameters in ϕ units)

This is the reverse of what would be expected if coarse till was to provide the initiating obstruction for a fluted moraine (c.f. Section 6.2.3) but the characteristic shape of these features is also the reverse of a fluted moraine, being highest at the distal end. (iii) Section 9.3 demonstrated that the till in samples from high, ice-moulded "ridges" was significantly coarser than that in samples from fluted moraines and hummocky moraines (Table 9.2.C). (The group named hummocky moraines does not include the features described at the end of Section 10.2 whose particle-size distributions were not

sampled.)

10.4.3 Possible explanations

Six possible explanations of the features are given below. The first two have been used by several authors to explain hummocky moraines but can be rejected comprehensively on the evidence presented in this project. The other four have been formulated in the context of this project but give less complete and more complicated solutions than the proposal described above.

(1) The published ideas describing how hummocky moraines can be formed from subglacially derived debris that has been elevated to the glacier surface were described in Section 3.4.1. They require that debris should be elevated gradually over a considerable distance as ice freezes to the glacier base and/or it requires a zone of longitudinally compressive flow where folding and faulting of the ice allows greater vertical movement. Neither of these conditions could apply in glacier source areas (Sections 6.3 and 8.3). Nor could the till respond as quickly as has been observed to bedrock changes if a period of englacial transport intervened between erosion and deposition. This is particularly true of samples taken from near the surface of the till which should contain the farthest travelled material (Boulton 1970b). Other reasons for rejection are that debris deposited from the surface of the ice could not be overlain by fluted moraines or be ice-moulded and would not display preferred clast orientations parallel to ice-flow (Section 5.3 and Chapter 7). Such features would be expected to include sorted deposits produced by melt water.

(2) There is no evidence to support the possibility of squeezing at the base of stagnant ice (till plateau and till fabrics orientated transverse to ridge crests (Hoppe 1952) or rectilinear ridge patterns (Gravenor and Kupsch 1959)). In some areas this explanation is specifically ruled out by evidence of active ice after formation of the features and in others by the alignment of till fabrics parallel to ridge crests. In general this explanation seems inapplicable to such a coarse-grained material and to features that are so close together.

(3) The dominance of very locally derived material in the till can be explained by applying De Geer's (1940) and Morner's (1978) finding that rapid isostatic recovery during deglaciation can cause fracturing. If this occurred a short time before deglaciation or a short distance up ice of the glacier snout the resulting debris could move only a short distance. This proposal would not explain the survival of ice-sheet erratics, which were available for transport at the start of the Loch Lomond Advance and would therefore require an additional explanation. It gives no mechanism for the formation of the hummocks and it requires that the moraines should be formed and their surfaces should be fluted at the very end of the glaciation.

(4) Another possibility is that permafrost may have formed before the glaciers advanced, holding the debris in place until the climate ameliorated at the end of the stadial. At that time the permafrost would be melted by water percolating through the wasting glacier. It could then be moved and formed into its present arrangement before deglaciation. This proposal is rejected because it seems unlikely that permafrost did develop before the glaciers advanced, because it provides no mechanism for formation of the

features and because it requires several processes to be carried out by active ice during deglaciation.

(5) One alternative explanation that attributes some of the formation of the features to glacier advance involves incorporation of debris into the ice near the glacier snout. Advance is punctuated by periods of retreat when this debris-charged ice wastes down. Renewed advance overrides the stagnant ice so that on deglaciation the till melts out to produce hummocks where it has been most concentrated with fluted surfaces where ice has overridden it. This proposal is rejected because it is considerably more complex than the preferred one. Deposition by melt-out also seems incompatible with the observed sharpness of the morphology and conspicuousness of dead-ice hollows.

(6) Another possibility is that the features were formed by the Late Devensian ice-sheet and subsequently overridden by the Loch Lomond Advance glaciers. The samples show that the debris has been carried in a variety of directions in different valleys. All these directions are consistent with the pattern of Loch Lomond Advance glaciation and some go against the SE-NW direction followed by the ice-sheet. However it was mentioned in Section 2.5 that a more local, radial pattern of flow may have existed during the late stages of the ice-sheet glaciation. Evidence such as the contrast between the percentages of ice-sheet erratics inside (c. 5 %) and outside (c. 25 %) the limit of the Loch Lomond Advance in Coire a Cheud Cnìoc (Section 7.5), and the impressive effects of local bedrock changes do not rule out the possibility that a readvance, of similar extent and configuration to the Loch Lomond Advance, took place during ice-sheet

retreat. However, since there is no evidence to support this suggestion and its adoption would make explanation of the features more complicated it is not considered further.

In summary, the first proposal explains all the generalisations made at the start of Section 10.4, it is relatively simple, all parts of the process can be accounted for, and some other evidence corroborates it.

10.5 Conclusions

The study has shown that within each of the two groups that have been called hummocky and fluted moraines there is a great variety of features and that there are ice-moulded hummocky moraines and hummocky moraines with fluted surfaces as well as ridges composed of strings of hummocky moraines. Thus all the features are members of a continuum and their origins are linked.

It has been shown that the hummocky moraines are composed of material derived from the valley floor that includes the deposits of the previous glaciation and very locally derived bedrock. The survival of material deposited by the previous glaciation in glacier source areas and the rapid changes of till lithology in response to bedrock types indicate that the till has travelled only a short distance during the Loch Lomond Advance and that glacial erosion in this area during that event has been slight. This evidence also suggests that the features were formed during a short period early in the glaciation. The presence of some ice-moulded hummocks and fluted moraines on the surface of others indicates the passage of active ice after their formation. The change in conditions that allowed formation of the features but prevented their subsequent

disappearance is most likely to have been at the onset of the glaciation, the relief of the features being attributable to pushing at the glacier snout and their detailed form being the result of lateral concentration during this process and subsequent ice-moulding. Several factors, stemming from characteristics of the material, the area and the glaciation, have been invoked to show that conditions were favourable for the survival of the features at the glacier base.

The position of some fluted moraines on the surfaces of hummocks and their alignment parallel to the probable direction of ice-flow at the maximum extent of the glaciers indicate that they were formed after the hummocks when the glaciers were close to their maximal limits. Some of them are composed of material that is farther-travelled than that in the underlying till while others seem to result from reworking of that material. This indicates that they are the result of a variety of depositional and erosional processes. The survival of these features, and the absence of retreat moraines suggest that the glaciers had low activity regimes during deglaciation.

10.6 Implications of the project

10.6.1 Implications concerning glacial transport

One incidental result of the study was the finding that the material in hummocky moraines had only been moved short distances during the Loch Lomond Advance. This was shown by the survival of ice-sheet erratics in glacier source areas and by the changes in rock-type composition of the till within short distances of bedrock

contacts. Examples of such changes within a few hundred metres were recorded in Sections 5.2, 5.3, 6.2, 8.2, 8.3, 8.4 and 8.5.

Many studies have provided evidence that till in areas covered by ice-sheets responds quickly to changes in bedrock lithology (Driemanis and Vagners 1969, Gross and Moran 1971, Linden 1975, and Haldorsen 1977). Of these the one that is most often quoted as an extreme example is Linden's finding that 3.5km down-ice of a bedrock change roughly 75 % of the till is composed of the local bedrock. Even allowing for the fact that only those particles over 1mm in diameter have been considered in this project, for reasons explained in Section 4.4, the results presented here are more extreme than those reported elsewhere. This may reflect the difference between the work of valley glaciers and ice-sheets. It could also be argued that it is due to the brevity of the Loch Lomond Advance, implying that if ice had been present longer the debris would have moved farther.

It is interesting that Whillans (1977) was prompted by the findings of Linden and others to write a speculative paper. He argued that the observed patterns indicated that ice-sheets transport most material a short distance (c. 10km) or that the material is comminuted to silt size and carried away by melt water within that distance. He rejected the second of these ideas after estimating the massive volume of erosion that it implied. In order to account for the preferred alternative he proposed that the break-up of bedrock was largely a pre-glacial process and that movement of the debris was limited to the first few decades after the ice front advanced over it. In these respects his theory corresponds to the view put forward

here but the mechanism he used to account for his proposals involved a complicated sequence of freezing and thawing and produced unlikely predictions e.g. "each glacier advance is capable of moving only the water-frozen regolith, which was probably only a metre or so thick" (P. 522).

The implications for glacial transport arising from this study cannot be fully developed until it is ^y established whether the results are a special case, only produced by valley glaciers or by short glaciations, or whether other deposits yield similar results.

10.6.2 Implications concerning fluted moraines

It will be clear from the foregoing discussions that fluted moraines have been extremely important as indicators of subglacial origin in this project. However, the contribution of the study to the understanding of fluted moraines is relatively limited. The general absence of rigid initiating obstructions at the proximal ends of the ridges and the "clast dominated" nature of some of them (making them unsuited to postdepositional deformation) indicate that Boulton's (1976) explanation of small-scale fluted moraines (Section 3.3.2) does not extend to these larger scale features. The fact that a large percentage of the material in the ridge studied in Section 6.2 was present before the Loch Lomond Advance implies that in this example the feature is largely a result of reworking rather than deposition of fresh material. The flutings on the surfaces of larger hummocky moraines in Chapter 7 are generally composed of material similar to that which they overlies; thus it seems likely that they were formed by reworking of that material. However the features

studied in Sections 5.2 and 5.3 were produced by deposition of material that contrasts with that below it.

The puzzling feature studied in Section 9.2.3 (Fig. 9.1, feature D) was only explained after assuming that ice flowed across a col which has no other evidence for its passage. Since the writer is not aware of any comparable features that have been described in the literature this example contributed new information but does not provide additional understanding.

10.6.3 Implications concerning hummocky moraines

The main implications of the study involve hummocky moraines. It was shown in Section 3.4.1 that the dominant explanation of such landscapes involves deposition from the ice surface. The conclusions of this study show that this explanation does not apply in the area studied. It could be argued that this area is a special case, that formation of the features was facilitated by the presence of faulted, well-jointed, coarse-grained bedrock and that the features survived because the glaciation was relatively short. However the evidence of ice-moulded hummocky moraines elsewhere in Scotland (Section 3.4.2) and the relationships noted between such features and subglacial landforms in other countries (e.g. Aario 1977, Markgren and Lassila 1980 and Hirvas 1977) indicate that the writer's explanation may be applied to other areas.

One special type of hummocky moraine that has often been studied is the Rogen moraine (Section 3.4.1). These are steep-sided ridges arranged transverse to ice-flow. To explain their morphology

early workers suggested a variety of origins before it was recognised that the features had been formed at the base of active ice. It is suggested that a similar impediment, based on the morphology of the landforms and aggravated by the establishment of a ruling hypothesis may have resulted in the misinterpretation of many hummocky glacial landscapes. Clearly such a weakness in the observational basis on which so much theoretical work concerning subglacial processes rests would have further important implications.

In a Scottish context it has been mentioned (Section 3.4.2) that hummocky moraines have often been used to delimit Loch Lomond Advance glaciers. This has led to criticisms that the origin of hummocky moraines must be more clearly understood and that the criteria for identifying such features must be improved. The last point is best illustrated by the debate about what are and are not hummocky moraines in the Cairngorms (e.g. Sissons 1974b, and Sugden 1980).

The origin of hummocky moraines has been one of the main concerns but the findings are not of direct relevance to the use of the features for mapping the extent of former glaciers. The main criterion for identifying hummocky moraines formed by Loch Lomond Advance glaciers has been the freshness of the features. Those features studied in this project have several other identifiable characteristics which include: an association with fluted moraines and a composition similar to them, an orderly streamlined form suggesting ice-moulding, an absence of sorted or bedded material and a close correspondence between rock-types in the till and the local bedrock. However it is likely that some Loch Lomond Advance glaciers produced hummocky moraines by other processes: hence failure to

fulfil these criteria does not mean that the features were formed by a different glaciation. Conversely the features described by Donner and West (1957) (Section 7.5) seem similar to some of the features studied here but lie outside the limit of the Loch Lomond Advance, showing that hummocky moraines of this type were not formed solely during that event.

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